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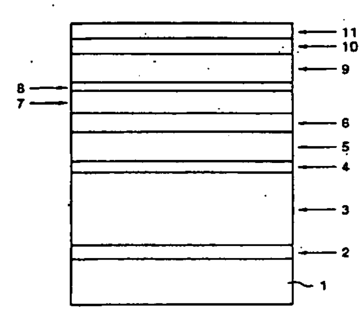
(54) Magnetic recording medium, magnetic storage apparatus, recording method and method of producing magnetic recording medium

(57) A magnetic recording medium is provided with at least one exchange layer structure, and a magnetic layer (9) formed on the exchange layer structure. The exchange layer structure includes a ferromagnetic layer (7) and a non-magnetic coupling layer (8) provided on the ferromagnetic layer (7) and under the magnetic layer (9).

FIG.1



EP 1 059 629 A2

Description

BACKGROUND OF THE INVENTION

1. Field of the Invention

[0001] The present invention generally relates to magnetic recording media and magnetic storage apparatuses, and more particularly to a magnetic recording medium and a magnetic storage apparatus which are suited for high-density recording. The present invention also relates to a recording method for magnetically recording information on a magnetic recording medium, and to a method of producing such a magnetic recording medium.

2. Description of the Related Art

[0002] The recording density of longitudinal magnetic recording media, such as magnetic disks, has been increased considerably, due to the reduction of medium noise and the development of magnetoresistive and high-sensitivity spin-valve heads. A typical magnetic recording medium is comprised of a substrate, an underlayer, a magnetic layer, and a protection layer which are successively stacked in this order. The underlayer is made of Cr or a Cr-based alloy, and the magnetic layer is made of a Co-based alloy.

[0003] Various methods have been proposed to reduce the medium noise. For example, Okamoto et al., "Rigid Disk Medium For 5 Gbit/in^2 Recording", AB-3, Intermag '96 Digest proposes decreasing the grain size and size distribution of the magnetic layer by reducing the magnetic layer thickness by the proper use of an underlayer made of CrMo, and a U.S. Patent No.5,693,426 proposes the use of an underlayer made of NiAl. Further, Hosoe et al., "Experimental Study of Thermal Decay in High-Density Magnetic Recording Media", IEEE Trans. Magn. Vol.33, 1528 (1997), for example, proposes the use of an underlayer made of CrTiB. The underlayers described above also promote c-axis orientation of the magnetic layer in a plane which increases the remanent magnetization and the thermal stability of written bits. In addition, proposals have been made to reduce the thickness of the magnetic layer, to increase the resolution or to decrease the transition width between written bits. Furthermore, proposals have been made to decrease the exchange coupling between grains by promoting more Cr segregation in the magnetic layer which is made of the CoCr-based alloy.

[0004] However, as the grains of the magnetic layer become smaller and more magnetically isolated from each other, the written bits become unstable due to thermal activation and to demagnetizing fields which increase with linear density. Lu et al., "Thermal Instability at 10 Gbit/in^2 Magnetic Recording", IEEE Trans. Magn. Vol.30, 4230 (1994) demonstrated, by micromagnetic simulation, that exchange-decoupled grains having a diameter of 10 nm and ratio K_uV/k_BT-60 in 400 kfci di-bits are susceptible to significant thermal decay, where K_u denotes the magnetic anisotropy constant, V denotes the average magnetic grain volume, k_B denotes the Boltzmann constant, and T denotes the temperature. The ratio K_uV/k_BT is also referred to as a thermal stability factor.

[0005] It has been reported in Abarra et al., "Thermal Stability of Narrow Track Bits in a 5 Gbit/in^2 Medium", IEEE Trans. Magn. Vol.33, 2995 (1997) that the presence of intergranular exchange interaction stabilizes written bits, by MFM studies of annealed 200 kfci bits on a 5 Gbit/in^2 CoCrPtTa/CrMo medium. However, more grain decoupling is essential for recording densities of 20 Gbit/in^2 or greater.

[0006] The obvious solution has been to increase the magnetic anisotropy of the magnetic layer. But unfortunately, the increased magnetic anisotropy places a great demand on the head write field which degrades the "overwrite" performance which is the ability to write over previously written data.

[0007] In addition, the coercivity of thermally unstable magnetic recording medium increases rapidly with decreasing switching time, as reported in He et al., "High Speed Switching in Magnetic Recording Media", J. Magn. Magn. Mater. Vol.155, 6 (1996), for magnetic tape media, and in J. H. Richter, "Dynamic Coervicity Effects in Thin Film Media", IEEE Trans. Magn. Vol.34, 1540 (1997), for magnetic disk media. Consequently, the adverse effects are introduced in the data rate, that is, how fast data can be written on the magnetic layer and the amount of head field required to reverse the magnetic grains.

[0008] On the other hand, another proposed method of improving the thermal stability increases the orientation ratio of the magnetic layer, by appropriately texturing the substrate under the magnetic layer. For example, Akimoto et al., "Relationship Between Magnetic Circumferential Orientation and Magnetic Thermal Stability", J. Magn. Magn. Mater. vol.193, pp.240-242(1999), in press, report through micromagnetic simulation, that the effective ratio K_uV/k_BT is enhanced by a slight increase in the orientation ratio. This further results in a weaker time dependence for the coercivity which improves the overwrite performance of the magnetic recording medium, as reported in Abarra et al., "The Effect of Orientation Ratio on the Dynamic Coercivity of Media for >15 Gbit/in^2 Recording", IEEE Trans. Magn. vol.35, pp.2709-2711, 1999.

[0009] Furthermore, keepered magnetic recording media have been proposed for thermal stability improvement.

The keeper layer is made up of a magnetically soft layer parallel to the magnetic layer. This soft layer can be disposed above or below the magnetic layer. Oftentimes, a Cr isolation layer is interposed between the soft layer and the magnetic layer. The soft layer reduces the demagnetizing fields in written bits on the magnetic layer. However, coupling the magnetic layer to a continuously-exchanged coupled soft layer defeats the purpose of decoupling the grains of the magnetic layer. As a result, the medium noise increases.

[0010] Various methods have been proposed to improve the thermal stability and to reduce the medium noise. However, there was a problem in that the proposed methods do not provide a considerable improvement of the thermal stability of written bits, thereby making it difficult to greatly reduce the medium noise. In addition, there was another problem in that some of the proposed methods introduce adverse effects on the performance of the magnetic recording medium due to the measures taken to reduce the medium noise.

[0011] More particularly, in order to obtain a thermally stable performance of the magnetic recording medium, it is conceivable to (i) increase the magnetic anisotropy constant K_u, (ii) decrease the temperature T or, (iii) increase the grain volume V of the magnetic layer. However, measure (i) increases the coercivity, thereby making it more difficult to write information on the magnetic layer. In addition, measure (ii) is impractical since in magnetic disk drives, for example, the operating temperature may become greater than 60° C. Furthermore, measure (iii) increases the medium noise as described above. As an alternative for measure (iii), it is conceivable to increase the thickness of the magnetic layer, but this would lead to deterioration of the resolution.

SUMMARY OF THE INVENTION

[0012] Accordingly, it is a general object of the present invention to provide a novel and useful magnetic recording medium, magnetic storage apparatus, recording method and method of producing magnetic recording medium, in which the problems described above are eliminated.

[0013] Another and more specific object of the present invention is to provide a magnetic recording medium, a magnetic storage apparatus, a recording method and a method of producing a magnetic recording medium, which can improve the thermal stability of written bits without increasing the medium noise, so as to enable reliable high-density recording without introducing adverse effects on the performance of the magnetic recording medium, that is, unnecessarily increasing the magnetic anisotropy.

[0014] Still another object of the present invention is to provide a magnetic recording medium comprising at least one exchange layer structure, and a magnetic layer formed on said exchange layer structure, where said exchange layer structure comprises a ferromagnetic layer, and a non-magnetic coupling layer provided on said ferromagnetic layer and under said magnetic layer. According to the magnetic recording medium of the present invention, it is possible to provide a magnetic recording medium which can improve the thermal stability of written bits, so as to enable reliable high-density recording without degrading the overwrite performance.

[0015] A further object of the present invention is to provide a magnetic recording medium comprising a substrate, an underlayer disposed above said substrate, and a magnetic layer structure including at least a bottom ferromagnetic layer provided on the underlayer and having a remanent magnetization and thickness product $Mr_i\delta_i$, and a top ferromagnetic layer disposed above the bottom ferromagnetic layer and having a remanent magnetization and thickness product $Mr_j\delta_j$, wherein a relationship $Mr\delta \fallingdotseq \Sigma(Mr_i\delta_i - Mr_j\delta_j)$ is satisfied, where $Mr\delta$ denotes a total remanent magnetization and thickness product of the magnetic layer structure, so that magnetization directions of adjacent ferromagnetic layers in the magnetic layer structure are closely antiparallel.

[0016] Another object of the present invention is to provide a method of magnetically recording information on a magnetic recording medium, comprising a step of switching magnetization direction of at least one of ferromagnetic layers which form a magnetic layer structure of the magnetic recording medium and have antiparallel magnetization directions.

[0017] Still another object of the present invention is to provide a method of producing a magnetic recording medium having a substrate, an underlayer and a magnetic layer structure, comprising the steps of (a) forming the magnetic layer structure to include at least a bottom ferromagnetic layer provided on the underlayer and having a remanent magnetization and thickness product $Mr_i\delta_i$, and a top ferromagnetic layer disposed above the bottom ferromagnetic layer and having a remanent magnetization and thickness product $Mr_j\delta_j$, wherein a relationship $Mr\delta \fallingdotseq \Sigma(Mr_i\delta_i - Mr_j\delta_j)$ is satisfied, where $Mr\delta$ denotes a total remanent magnetization and thickness product of the magnetic layer structure, so that magnetization directions of adjacent ferromagnetic layers in the magnetic layer structure are closely antiparallel, and (b) forming the underlayer and the magnetic structure by sequential (continuous) sputtering.

[0018] A further object of the present invention is to provide a magnetic recording medium comprising at least one exchange layer structure and a magnetic layer provided on the exchange layer structure, the exchange layer structure including a ferromagnetic layer and a non-magnetic coupling layer provided on the ferromagnetic layer, and a magnetic bonding layer provided between the ferromagnetic layer and the non-magnetic coupling layer and/or between the non-magnetic coupling layer and the magnetic layer, the magnetic bonding layer having a magnetization direction parallel to

the ferromagnetic layer and the magnetic layer. According to the magnetic recording medium of the present invention, it is possible to provide a magnetic recording medium which can improve the thermal stability of written bits, so as to enable reliable high-density recording without degrading the overwrite performance.

[0019] Another object of the present invention is to provide a magnetic recording medium characterized by at least one exchange layer structure; and a magnetic layer formed on the exchange layer structure, the exchange layer structure comprising a ferromagnetic layer, and a non-magnetic coupling layer provided on the ferromagnetic layer and under the magnetic layer, the ferromagnetic layer and the magnetic layer having antiparallel magnetizations, and the non-magnetic coupling layer being made of a Ru-M3 alloy, where M3 is an added element or alloy, and a lattice mismatch between the non-magnetic coupling layer and the magnetic layer and the ferromagnetic layer respectively disposed above and below the non-magnetic coupling layer is adjusted to approximately 6% or less by addition of M3. According to the magnetic recording medium of the present invention, it is possible to provide a magnetic recording medium which can improve the thermal stability of written bits, so as to enable reliable high-density recording without degrading the overwrite performance, and to improve the recording resolution by improving the in-plane crystal orientation of the magnetic layer.

[0020] Still another object of the present invention is to provide a magnetic recording medium characterized by at least one exchange layer structure; and a magnetic layer formed on the exchange layer structure, the exchange layer structure comprising a ferromagnetic layer, and a non-magnetic coupling layer provided on the ferromagnetic layer and under the magnetic layer, the ferromagnetic layer and the magnetic layer having antiparallel magnetizations, the non-magnetic coupling layer being made of a Ru-M3 alloy, where M3 = Co, Cr, Fe, Ni, Mn or alloys thereof. According to the magnetic recording medium of the present invention, it is possible to provide a magnetic recording medium which can improve the thermal stability of written bits, so as to enable reliable high-density recording without degrading the overwrite performance, and to improve the recording resolution by improving the in-plane crystal orientation of the magnetic layer.

[0021] A further object of the present invention is to provide a magnetic recording medium comprising a substrate, an underlayer disposed above the substrate, and a magnetic recording layer disposed above the underlayer, where the magnetic recording layer has a multi-layer structure which is separated into at least upper and lower layers by a non-magnetic separation layer, the non-magnetic separation layer is made of a material selected from a group of Ru, Rh, Ir and alloys thereof, and the upper and lower layers of the multi-layer structure separated by the non-magnetic separation layer have magnetization directions which are mutually parallel. According to the magnetic recording medium of the present invention, the non-magnetic separation layer which is made of Ru or the like and has a predetermined thickness maintains the magnetic coupling of magnetic recording layers above and below the non-magnetic separation layer to a mutually parallel state. Hence, it is possible to realize a magnetic recording medium having low noise and desired thermal stability. Compared to the conventional magnetic recording medium, this magnetic recording medium has a high reliability and is suited for high-density recording.

[0022] Another object of the present invention is to provide a magnetic recording medium comprising at least one exchange layer structure and a magnetic layer provided on the exchange layer structure, where the exchange layer structure includes a ferromagnetic layer and a non-magnetic coupling layer provided on the ferromagnetic layer, at least one of the ferromagnetic layer and the magnetic layer has a granular layer structure in which ferromagnetic crystal grains are uniformly distributed within a non-magnetic base material. According to the magnetic recording medium of the present invention, it is possible to provide a magnetic recording medium which can improve the thermal stability of written bits, so as to enable reliable high-density recording without degrading the overwrite performance. By employing the granular layer structure which is effective in reducing noise for at least the ferromagnetic layer of the exchange layer structure and the magnetic layer which is provided on the exchange layer structure, it is possible to further reduce the medium noise while further improving the thermal stability of the written bits.

[0023] The magnetic recording medium may comprise at least a first exchange layer structure and a second exchange layer structure provided between the first exchange layer structure and the magnetic layer, where the first and second exchange layer structures have a granular layer structure, the second exchange layer structure has a granular layer with a magnetic anisotropy smaller than that of a granular layer of the first exchange layer structure, and the granular layers of the first and second exchange layer structures have magnetization directions which are mutually antiparallel.

[0024] The magnetic recording medium may comprise at least a first exchange layer structure and a second exchange layer structure provided between the first exchange layer structure and the magnetic layer, where the first and second exchange layer structures have a granular layer structure, the second exchange layer structure has a granular layer with a remanence magnetization and thickness product smaller than that of a granular layer of the first exchange layer structure, and the granular layers of the first and second exchange layer structures have magnetization directions which are mutually antiparallel.

[0025] Still another object of the present invention is to provide a magnetic storage apparatus comprising at least one magnetic recording medium of any one of the types described above. According to the magnetic storage apparatus

of the present invention, it is possible to provide a magnetic storage apparatus which can improve the thermal stability of written bits, so as to enable a reliable high-density recording without introducing adverse effects on the performance of the magnetic recording medium.

[0026] Other objects and further features of the present invention will be apparent from the following detailed description when read in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0027]

FIG. 1 is a cross sectional view showing an important part of a first embodiment of the magnetic recording medium according to the present invention;
FIG. 2 is a cross sectional view showing an important part of a second embodiment of the magnetic recording medium according to the present invention;
FIG. 3 is a diagram showing an in-plane magnetization curve of a single CoPt layer having a thickness of 10 nm on a Si substrate;
FIG. 4 is a diagram showing an in-plane magnetization curve of two CoPt layers separated by a Ru layer having a thickness of 0.8 nm;
FIG. 5 is a diagram showing an in-plane magnetization curve of two CoPt layers separated by a Ru layer having a thickness of 1.4 nm;
FIG. 6 is a diagram showing an in-plane magnetization curve two CoCrPt layers separated by a Ru having a thickness of 0.8 nm;
FIG. 7 is a cross sectional view showing an important part of an embodiment of the magnetic storage apparatus according to the present invention;
FIG. 8 is a plan view showing the important part of the embodiment of the magnetic storage apparatus;
FIG. 9 is a diagram showing an in-plane magnetization curve for a magnetic recording medium having a single CoCrPtB layer grown on a NiAl layer on glass;
FIG. 10 is a diagram showing an in-plane magnetization curve for a magnetic recording medium having two ferromagnetic layers of CoCrPtB separated by a Ru layer having a thickness of 0.8 nm on a NiP coated Al-Mg substrate;
FIG. 11 is a diagram showing an in-plane magnetization curve for a magnetic recording medium having two ferromagnetic layers of CoCrPtB separated by a Ru layer on a NiP coated Al substrate;
FIG. 12 is a diagram showing an in-plane magnetization curve for a magnetic recording medium having three ferromagnetic layers of CoCrPtB separated by a Ru layer between each two adjacent CoCrPtB layers on a NiP coated Al substrate;
FIG. 13 is a diagram showing an in-plane magnetization curve for a magnetic recording medium having two negatively coupled ferromagnetic layers of CoCrPtB separated by a Ru layer, on a NiAl coated glass substrate;
FIG. 14 is a diagram showing an in-plane magnetization curve shown in FIG. 13 in comparison with a magnetic recording medium having a single ferromagnetic layer of CoCrPtB on a NiAl coated glass substrate;
FIG. 15 is a diagram showing signal decays of the magnetic recording media having two and three ferromagnetic layers, in comparison with a signal decay of the magnetic recording medium having the single ferromagnetic layer;
FIG. 16 is a diagram showing M-H curves of the magnetic recording medium having the two negatively coupled ferromagnetic layers at different temperatures;
FIG. 17 is a diagram showing the temperature dependence of the coercivity for the magnetic recording medium having the characteristics shown in FIG. 16;
FIG. 18 is a diagram showing the PW50 dependence on the effective and total ferromagnetic layer thickness of the magnetic recording media having one, two and three ferromagnetic layers;
FIG. 19 is a diagram showing the effective thickness dependence of the change in isolated wave medium SNR;
FIG. 20 is a diagram showing the general construction of a magnetic recording medium producing apparatus;
FIG. 21 is a diagram showing the dependence of isolated wave output on magnetic layer thickness;
FIG. 22 is a diagram showing the temperature dependence of high-frequency SNR;
FIG. 23 is a diagram showing a relation ship of the isolated wave medium SNR Siso/Nm and the sputtering rate of Ru;
FIG. 24 is a cross sectional view showing an important part of a fourth embodiment of the magnetic recording medium according to the present invention;
FIG. 25 is a diagram for explaining in-plane characteristics of two CoCr-based alloy layers separated by Ru;
FIG. 26 is a cross sectional view showing an important part of a fifth embodiment of the magnetic recording medium according to the present invention;
FIG. 27 is a diagram showing a magnetization curve which is obtained when pure Ru is used for a non-magnetic

coupling layer of the magnetic recording medium;

FIG. 28 is a diagram showing a magnetization curve which is measured by a vertical Kerr looper while applying a magnetic field in a perpendicular direction with respect to a sample surface;

FIG. 29 is a cross sectional view showing an important part of a sixth embodiment of the magnetic recording medium according to the present invention;

FIG. 30 is a diagram showing the relationship of a ratio Siso/Nm of the isolated wave output (Siso) and medium noise (Nm) of the sixth embodiment of the magnetic recording medium and the thickness of a Ru non-magnetic separation layer;

FIG. 31 is a diagram showing the relationship of a thickness ratio of first and second magnetic recording layers and the ratio Siso/Nm of the isolated wave output (Siso) and medium noise (Nm);

FIG. 32 is a diagram showing the relationship of the thickness ratio of the first and second magnetic recording layers and a ratio S/Nt of an output (S) and noise (Nt); and

FIG. 33 is a cross sectional view showing an important part of a seventh embodiment of the magnetic recording medium according to the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0028] A description will hereinafter be given of embodiments of the present invention, by referring to the drawings.

[0029] First, a description will be given of the operating principle of the present invention.

[0030] The present invention submits the use of layers with antiparallel magnetization structures. For example, S. S. P. Parkin, "Systematic Variation of the Strength and Oscillation Period of Indirect Magnetic Exchange Coupling through the 3d, 4d, and 5d Transition Metals", Phys. Rev. Lett. Vol.67, 3598 (1991) describes several magnetic transition metals such as Co, Fe and Ni that are coupled through thin non-magnetic interlayers such as Ru and Rh. On the other hand, a U.S. Patent No.5,701,223 proposes a spin-valve which employs the above described layers as laminated pinning layers to stabilize the sensor.

[0031] For a particular Ru or Ir layer thickness between two ferromagnetic layers, the magnetizations can be made parallel or antiparallel. For example, for a structure made up of two ferromagnetic layers of different thickness with antiparallel magnetizations, the effective grain size of a magnetic recording medium can be increased without significantly affecting the resolution. A signal amplitude reproduced from such a magnetic recording medium is reduced due to the opposite magnetizations, but this can be rectified by adding another layer of appropriate thickness and magnetization direction, under the laminated magnetic layer structure, to thereby cancel the effect of one of the layers. As a result, it is possible to increase the signal amplitude reproduced from the magnetic recording medium, and to also increase the effective grain volume. Thermally stable written bits can therefore be realized.

[0032] The present invention increases the thermal stability of written bits by exchange coupling the magnetic layer to another ferromagnetic layer with an opposite magnetization or, by a laminated ferrimagnetic structure. The ferromagnetic layer or the laminated ferrimagnetic structure is made up of exchange-decoupled grains as the magnetic layer. In other words, the present invention uses an exchange pinning ferromagnetic layer or a ferrimagnetic multilayer to improve the thermal stability performance of the magnetic recording medium.

[0033] FIG. 1 is a cross sectional view showing an important part of a first embodiment of a magnetic recording medium according to the present invention.

[0034] The magnetic recording medium includes a non-magnetic substrate 1, a first seed layer 2, a NiP layer 3, a second seed layer 4, an underlayer 5, a non-magnetic intermediate layer 6, a ferromagnetic layer 7, a non-magnetic coupling layer 8, a magnetic layer 9, a protection layer 10, and a lubricant layer 11 which are stacked in the order shown in FIG. 1.

[0035] For example, the non-magnetic substrate 1 is made of Al, Al alloy or glass. This non-magnetic substrate 1 may or may not be mechanically textured. The first seed layer 2 is made of Cr or Ti, for example, especially in the case where the non-magnetic substrate 1 is made of glass. The NiP layer 3 is preferably oxidized and may or may not be mechanically textured. The second seed layer 4 is provided to promote a (001) or a (112) texture of the underlayer 5 when using a B2 structure alloy such as NiAl and FeAl for the underlayer 5. The second seed layer 4 is made of an appropriate material similar to that of the first seed layer 2.

[0036] In a case where the magnetic recording medium is a magnetic disk, the mechanical texturing provided on the non-magnetic substrate 1 or the NiP layer 3 is made in a circumferential direction of the disk, that is, in a direction in which tracks of the disk extend.

[0037] The non-magnetic intermediate layer 6 is provided to further promote epitaxy, narrow the grain distribution of the magnetic layer 9, and orient the anisotropy axes of the magnetic layer 9 along a plane parallel to the recording surface of the magnetic recording medium. This non-magnetic intermediate layer 6 is made of a hcp structure alloy such as CoCr-M, where M = B, Mo, Nb, Ta, W, Cu or alloys thereof, and has a thickness in a range of 1 to 5 nm.

[0038] The ferromagnetic layer 7 is made of Co, Ni, Fe, Co-based alloy, Ni-based alloy, Fe-based alloy or the like.

In other words, alloys such as CoCrTa, CoCrPt and CoCrPt-M, where M = B, Mo, Nb, Ta, W, Cu or alloys thereof may be used for the ferromagnetic layer 7. This ferromagnetic layer 7 has a thickness in a range of 2 to 10 nm. The non-coupling magnetic layer 8 is made of Ru, Ir, Rh, Cr, Cu, Ru-based alloy, Ir-based alloy, Rh-based alloy, Cu-based alloy, Cr-based alloy or the like. This non-magnetic coupling layer 8 preferably has a thickness in a range of 0.4 to 1.0 nm for antiparallel coupling using Ru, and preferably on the order of approximately 0.6 to 0.8 nm for an antiparallel coupling using Ru. For this particular thickness range of the non-magnetic coupling layer 8, the magnetizations of the ferromagnetic layer 7 and the magnetic layer 9 are antiparallel. The ferromagnetic layer 7 and the non-magnetic coupling layer 8 form an exchange layer structure.

[0039] For a ferromagnetic layer 7 made of a Fe-based alloy, Cr forms a better non-magnetic coupling layer 8. In this case, the Cr non-magnetic coupling layer 8 has an optimum thickness of approximately 1.8 nm.

[0040] The magnetic layer 9 is made of Co or a Co-based alloys such as CoCrTa, CoCrPt and CoCrPt-M, where M = B, Mo, Nb, Ta, W, Cu or alloys thereof. The magnetic layer 9 has a thickness in a range of 5 to 30 nm. Of course, the magnetic layer 9 is not limited to a single-layer structure, and a multi-layer structure may be used for the magnetic layer 9.

[0041] The protection layer 10 is made of C, for example. In addition, the lubricant layer 11 is made of an organic lubricant, for example, for use with a magnetic transducer such as a spin-valve head. The protection layer 10 and the lubricant layer 11 form a protection layer structure on the recording surface of the magnetic recording medium.

[0042] Obviously, the layer structure under the exchange layer structure is not limited to that shown in FIG. 1. For example, the underlayer 5 may be made of Cr or Cr-based alloy and formed to a thickness in a range of 5 to 40 nm on the substrate 1, and the exchange layer structure may be provided on this underlayer 5.

[0043] Next, a description will be given of a second embodiment of the magnetic recording medium according to the present invention.

[0044] FIG. 2 is a cross sectional view showing an important part of the second embodiment of the magnetic recording medium. In FIG. 2, those parts which are the same as those corresponding parts in FIG. 1 are designated by the same reference numerals, and a description thereof will be omitted.

[0045] In this second embodiment of the magnetic recording medium, the exchange layer structure includes two non-magnetic coupling layers 8 and 8-1, and two ferromagnetic layers 7 and 7-1, which form a ferrimagnetic multilayer. This arrangement increases the effective magnetization and signal, since the magnetizations of the two non-magnetic coupling layers 8 and 8-1 cancel each other instead of a portion of the magnetic layer 9. As a result, the grain volume and thermal stability of magnetization of the magnetic layer 9 are effectively increased. More bilayer structures made up of the pair of ferromagnetic layer and non-magnetic coupling layer may be provided additionally to increase the effective grain volume, as long as the easy axis of magnetization are appropriately oriented for the subsequently provided layers.

[0046] The ferromagnetic layer 7-1 is made of a material similar to that of ferromagnetic layer 7, and has a thickness range selected similarly to the ferromagnetic layer 7. In addition, the non-magnetic coupling layer 8-1 is made of a material similar to that of the non-magnetic coupling layer 8, and has a thickness range selected similarly to the non-magnetic coupling layer 8. Within the ferromagnetic layers 7-1 and 7, the c-axes are preferably in-plane and the grain growth columnar.

[0047] In this embodiment, the magnetic anisotropy of the ferromagnetic layer 7-1 is preferably higher than that of the ferromagnetic layer 7. However, the magnetic anisotropy of the ferromagnetic layer 7-1 may be the same as or, be higher than that of, the magnetic layer 9.

[0048] Furthermore, a remanent magnetization and thickness product of the ferromagnetic layer 7 may be smaller than that of the ferromagnetic layer 7-1.

[0049] FIG. 3 is a diagram showing an in-plane magnetization curve of a single CoPt layer having a thickness of 10 nm on a Si substrate. In FIG. 3, the ordinate indicates the magnetization (emu), and the abscissa indicates the magnetic field (Oe). Conventional magnetic recording media show a behavior similar to that shown in FIG. 3.

[0050] FIG. 4 is a diagram showing an in-plane magnetization curve of two CoPt layers separated by a Ru layer having a thickness of 0.8 nm, as in the case of the first embodiment of the magnetic recording medium. In FIG. 4, the ordinate indicates the magnetization (Gauss), and the abscissa indicates the magnetic field (Oe). As may be seen from FIG. 4, the loop shows shifts near the magnetic field which indicate the antiparallel coupling.

[0051] FIG. 5 is a diagram showing an in-plane magnetization curve of two CoPt layers separated by a Ru layer having a thickness of 1.4 nm. In FIG. 5, the ordinate indicates the magnetization (emu), and the abscissa indicates the magnetic field (Oe). As may be seen from FIG. 5, the magnetizations of the two CoPt layers are parallel.

[0052] FIG. 6 is a diagram showing an in-plane magnetization curve for two CoCrPt layers separated by a Ru having a thickness of 0.8 nm, as in the case of the second embodiment of the magnetic recording medium. In FIG. 6, the ordinate indicates the magnetization (emu/cc), and the abscissa indicates the field (Oe). As may be seen from FIG. 6, the loop shows shifts near the field which indicate the antiparallel coupling.

[0053] From FIGS. 3 and 4, it may be seen that the antiparallel coupling can be obtained by the provision of the

exchange layer structure. In addition, it may be seen by comparing FIG. 5 with FIGS. 4 and 6, the non-magnetic coupling layer 8 is desirably in the range of 0.4 to 1.0 nm in order to achieve the antiparallel coupling.

[0054] Therefore, according to the first and second embodiments of the magnetic recording medium, it is possible to effectively increase the apparent grain volume of the magnetic layer by the exchange coupling provided between the magnetic layer and the ferromagnetic layer via the non-magnetic coupling layer, without sacrificing the resolution. In other words, the apparent thickness of the magnetic layer is increased with regard to the grain volume of the magnetic layer so that a thermally stable medium can be obtained, and in addition, the effective thickness of the magnetic layer is maintained since cancellation of signals especially from the bottom layers is achieved. This allows higher linear density recording that is otherwise not possible for thick media. As a result, it is possible to obtain a magnetic recording medium with reduced medium noise and thermally stable performance.

[0055] Next, a description will be given of an embodiment of a magnetic storage apparatus according to the present invention, by referring to FIGS. 7 and 8. FIG. 7 is a cross sectional view showing an important part of this embodiment of the magnetic storage apparatus, and FIG. 8 is a plan view showing the important part of this embodiment of the magnetic storage apparatus.

[0056] As shown in FIGS. 7 and 8, the magnetic storage apparatus generally includes a housing 13. A motor 14, a hub 15, a plurality of magnetic recording media 16, a plurality of recording and reproducing heads 17, a plurality of suspensions 18, a plurality of arms 19, and an actuator unit 20 are provided within the housing 13. The magnetic recording media 16 are mounted on the hub 15 which is rotated by the motor 14. The recording and reproducing head 17 is made up of a reproducing head such as a MR or GMR head, and a recording head such as an inductive head. Each recording and reproducing head 17 is mounted on the tip end of a corresponding arm 19 via the suspension 18. The arms 19 are moved by the actuator unit 20. The basic construction of this magnetic storage apparatus is known, and a detailed description thereof will be omitted in this specification.

[0057] This embodiment of the magnetic storage apparatus is characterized by the magnetic recording media 16. Each magnetic recording medium 16 has the structure of the first or second embodiment of the magnetic recording medium described above in conjunction with FIGS. 1 and 2. Of course, the number of magnetic recording media 16 is not limited to three, and only one, two or four or more magnetic recording media 16 may be provided. Further, each magnetic recording medium 16 may have the structure of any of the embodiments of the magnetic recording medium which will be described later.

[0058] The basic construction of the magnetic storage unit is not limited to that shown in FIGS. 7 and 8. In addition, the magnetic recording medium used in the present invention is not limited to a magnetic disk.

[0059] Next, a description will be given of further features of the present invention, in comparison with the conventional magnetic recording medium having no exchange layer structure. In the following description, the ferromagnetic layer of the exchange layer structure and the magnetic layer will also be referred to as ferromagnetic layers forming a magnetic layer structure.

[0060] FIG. 9 is a diagram showing an in-plane magnetization curve for a magnetic recording medium having a single layer of CoCrPtB grown on a NiAl layer on glass. In FIG. 9, the ordinate indicates the magnetization M (emu/cc), and the abscissa indicates the magnetic field H (Oe). Similar M-H curves are observed for a single Co-based layer grown on a Cr underlayer on NiP coated Al substrate or NiP coated glass substrate.

[0061] On the other hand, FIG. 10 is a diagram showing an in-plane magnetization curve for a magnetic recording medium having two ferromagnetic layers of CoCrPtB separated by a Ru layer having a thickness of 0.8 nm, sputtered on a NiP coated Al-Mg substrate. In FIG. 10, the ordinate indicates the magnetization M (emu/cc), and the abscissa indicates the magnetic field H (Oe). As may be seen from FIG. 10, the magnetization M abruptly decreases when the magnetic field H is around H=500 Oe which indicates an exchange coupling field of approximately 1000 Oe. The reduced magnetization M at H=0 evidences the anti-parallel coupling.

[0062] The optimum Ru thickness for the negative coupling can be determined not only by magnetometry but also by spin stand methods. The reproduced signal at low densities gives an indication of a remanent magnetization and thickness product Mrδ, where Mr denotes the remanent magnetization and δ denotes the effective thickness of the CoCrPtB layer, that is, the ferromagnetic layer of the magnetic layer structure. If the Ru thickness is varied while the thicknesses of the two CoCrPtB layers are maintained constant, the reproduced signal shows a dip at the optimum Ru thickness. The optimum Ru thickness may depend on the magnetic materials and the processing used to form the ferromagnetic layers of the magnetic layer structure. For CoCrPt-based alloys manufactured above 150°C, the antiparallel coupling is induced for the Ru thickness in a range of approximately 0.4 to 1.0 nm.

[0063] FIG. 11 is a diagram showing an in-plane magnetization curve for a magnetic recording medium having two ferromagnetic layers of CoCrPtB separated by a Ru layer, on a NiP coated Al substrate. In FIG. 11, the ordinate indicates the magnetization M (emu/cc), and the abscissa indicates the magnetic field H (Oe). FIG. 11 shows a case where a first CoCrPtB layer closer to the substrate is 8 nm thick, the Ru layer is 0.8 nm thick, and a second CoCrPtB layer further away from the substrate is 20 nm thick.

[0064] In this case, antiparallel coupling is observed but at higher negative magnetic fields. Unless the demagnet-

izing fields inside bits are very high, the antiparallel coupling is not completely achieved and very high reproduced signals are observed as the magnetizations in both the first and second CoCrPtB layers point in essentially the same direction. It is therefore necessary to reduce the coercivity Hc of the first CoCrPtB layer by reducing the thickness thereof or, by use of compositions which result in a lower coercivity Hc. For CoCrPt-based materials, the latter is usually achieved by increasing the Cr content and/or reducing the Pt content.

[0065] FIG. 12 is a diagram showing an in-plane magnetization curve for a magnetic recording medium having three ferromagnetic layers of CoCrPtB separated by a Ru layer between each two adjacent CoCrPtB layers, on a NiP coated Al substrate. In FIG. 12, the ordinate indicates the magnetization M (emu/cc), and the abscissa indicates the magnetic field H (Oe). FIG. 12 shows a case where first and second CoCrPtB layers closer to the substrate are 6 nm thick, a top third CoCrPtB layer is 20 nm thick, and the Ru layers between the first and second CoCrPtB layers and between the second and third CoCrPtB layers respectively are 0.8 nm thick. In this case, the magnetization M drops when the magnetic field H is H=500 Oe, which indicates that one of the first through third CoCrPtB layers reversed magnetization at positive fields. It is likely the middle second CoCrPtB layer which reversed magnetization since this middle second CoCrPtB layer is subject to a stronger reversing field due to the two interfaces. The interlayer interaction is therefore 500 Oe greater than the coercivity Hc of the middle second CoCrPtB layer.

[0066] However, at low negative magnetic fields, the bottom first CoCrPtB layer starts reversing magnetization, such that at approximately -1000 Oe, the magnetization of only the top third CoCrPtB layer is not reversed. Preferably, the bottom first CoCrPtB layer should not reverse magnetization at magnetic fields which are low compared to the demagnetizing fields inside bits, and this may be achieved for example by choosing the proper thickness and/or composition for the bottom first CoCrPtB layer. The magnetic recording medium which has these three ferromagnetic layers tend to have read-write performance which is better than the magnetic recording medium which only has a single ferromagnetic (magnetic) layer with no exchange coupling. There is a possibility that the reproduced signal will be reduced with time as more grains change layer magnetization configuration from parallel to antiparallel which is more stable. However, a solitary wave media signal-to-noise ratio (SNR) Siso/Nm of the magnetic recording medium is expected to be maintained since the medium noise level is also correspondingly reduced. Hence, the bit error rate (BER) which is intimately related to the isolated wave medium SNR Siso/Nm will not be degraded.

[0067] FIG. 13 is a diagram showing an in-plane magnetization curve for a magnetic recording medium having two negatively coupled ferromagnetic layers of CoCrPtB separated by a Ru layer, on a NiAl coated glass substrate. In FIG. 13, the ordinate indicates the magnetization M (emu/cc), and the abscissa indicates the magnetic field H (Oe). As shown in FIG. 13, the bottom CoCrPtB layer closer to the substrate reverses magnetization even before the magnetic field H becomes H=0 Oe.

[0068] FIG. 14 is a diagram showing an in-plane magnetization curve shown in FIG. 13 in comparison with a magnetic recording medium having a single ferromagnetic layer of CoCrPtB on a NiAl coated glass substrate fabricated similarly to the recording medium having the two negatively coupled ferromagnetic layers. In FIG. 14, the ordinate indicates the magnetization M (emu/cc), and the abscissa indicates the magnetic field H (Oe). In FIG. 14, the in-plane magnetization curve shown in FIG. 13 is indicated by a solid line, and an in-plane magnetization curve for the recording medium with the single ferromagnetic layer is indicated by a dashed line. In FIG. 14, the saturation magnetization is normalized so as to illustrate the similarity of the M-H curve portions relevant to the magnetic recording.

[0069] When a head saturates a portion of the magnetic recording medium having the two negatively coupled ferromagnetic layers, the magnetization of both the two ferromagnetic layers is in the head field direction, but as soon as the head field is no longer applied, the bottom ferromagnetic layer reverses magnetization and the situation inside a bit would be similar to that of the magnetic recording medium having the single ferromagnetic layer. A read head only senses the resultant magnetization. A person skilled in the art can therefore tune the thickness, composition and processing of the ferromagnetic layers, so that the magnetic recording medium behaves similarly to the conventional magnetic recording medium but with an enhanced thermal stability.

[0070] FIG. 15 is a diagram showing signal decays of the magnetic recording media having two and three ferromagnetic layers, in comparison with a signal decay of the magnetic recording medium having the single ferromagnetic layer. In FIG. 15, the ordinate indicates the signal decay (dB) of the reproduced signal for 207 kfci bits, and the abscissa indicates the time (s). In FIG. 15, ◊ indicates the data of the magnetic recording medium having the single CoCrPtB layer which is 10 nm thick, ● indicates the data of the magnetic recording medium having the bottom first CoCrPtB layer which is 10 nm thick, the Ru layer which is 0.8 nm thick and the top second CoCrPtB layer which is 4 nm thick, and □ indicates the data of the magnetic recording medium having the bottom first CoCrPtB layer which is 10 nm thick, the first Ru layer which is 0.8 nm thick, the middle CoCrPtB layer which is 4 nm thick, the second Ru layer which is 0.8 nm thick and the top third CoCrPtB layer which is 4 nm thick. The ferromagnetic layer compositions are all the same, and the coercivity Hc measured with a Kerr magnetometer are approximately 2700 Oe (214.8 kA/m) and are similar. As may be seen from FIG. 15, the magnetic recording media having two ferromagnetic layers and three ferromagnetic layers show more thermally stable characteristics as the effective volume is increased, as compared to the magnetic recording medium having the single ferromagnetic layer and no exchange coupling.

[0071] FIG. 16 is a diagram showing M-H curves of the magnetic recording medium having the two negatively coupled ferromagnetic layers at different temperatures. In FIG. 16, the ordinate indicates the magnetization M (emu/cc), the abscissa indicates the magnetic field H (Oe), and the data are shown for three different temperatures which are 0°C, 25°C and 75°C. A strong negative coupling is observed over a wide temperature range, and covers the range useful for magnetic recording media such as disks and tapes.

[0072] FIG. 17 is a diagram showing the temperature dependence of the coercivity for the magnetic recording medium having the characteristics shown in FIG. 16. In FIG. 17, the ordinate indicates the coercivity Hc (Oe), and the abscissa indicates the measured temperature (°C). In addition, y=Hc and x=temperature in the expression y=-15.47x+4019.7. The coercivity change with temperature dHc/dT=15.5 Oe/°C and is less than that of the magnetic recording medium having the single ferromagnetic layer. A typical dHc/dT for the magnetic recording medium having the single ferromagnetic layer is 16 to 17 Oe/°C. Accordingly, it may be clearly seen that the improved dHc/dT value obtained for the magnetic recording medium having the two negatively coupled ferromagnetic layers primarily arises from the increased effective volume.

[0073] FIG. 18 is a diagram showing the PW50 dependence on the effective and total ferromagnetic layer thickness of the magnetic recording media having two and three ferromagnetic layers, in comparison with the PW50 dependence on the effective and total ferromagnetic layer thickness of the magnetic recording medium having the single ferromagnetic layer. In FIG. 18, the ordinate indicates the PW50 (ns), and the abscissa indicates the effective and total ferromagnetic layer thickness (nm). In FIG. 18, ♦ indicates the data of the magnetic recording medium having the single ferromagnetic layer, ■ indicates the data of the magnetic recording medium having two exchange-coupled ferromagnetic layers, and △ indicates the data of the magnetic recording medium having three exchange-coupled ferromagnetic layers. The thickness and composition of the ferromagnetic layers are basically the same as those used to obtain the data shown in FIG. 15. For the data on the left side along the solid line, the thickness used is the effective thickness, that is, magnetization cancellation due to an antiparallel configuration is assumed. Significant correlation is observed validating the assumption. When the total thickness of the ferromagnetic layer or layers is used, the data shifts to the right along the dotted line, which give unreasonably small PW50 values for the thicknesses involved when compared to those of the magnetic recording medium having the single ferromagnetic layer.

[0074] Therefore, although the writing resolution may be degraded due to the increased media thickness, the reading resolution is not, since cancellation of the signals from the lower layers occurs which may also explain the improved isolated wave medium SNR Siso/Nm over the magnetic recording medium having the single ferromagnetic layer. The isolated wave medium SNR Siso/Nm of the magnetic recording medium having the two exchange-coupled ferromagnetic layers and very low effective Mrδ is especially improved over that of the magnetic recording medium having the single ferromagnetic layer. Such a very low effective Mrδ can be achieved when the two ferromagnetic layers have almost the same Mrδ. For the magnetic recording medium having the three exchange-coupled ferromagnetic layers, the performance is enhanced when the sum of the thicknesses of the bottom first and middle second ferromagnetic layers is not so different from the thickness of the top third ferromagnetic layer. This phenomenon is consistent with a similar phenomenon which occurs in double uncoupled layers since the best thickness combination of the double uncoupled layers is when both layers are of the same thickness.

[0075] FIG. 19 is a diagram showing the effective thickness dependence of the change in isolated wave medium SNR. In FIG. 19, the ordinate indicates the change △Siso/Nm (dB) of the isolated wave medium SNR Siso/Nm, and the abscissa indicates the effective thickness (nm) of the ferromagnetic layers. In FIG. 19, the same symbols ♦, ■ and △ are used to indicate the data of the three different magnetic recording media as in FIG. 18. It may be seen from FIG. 19 that good isolated wave medium SNR Siso/Nm is especially observed for the magnetic recording medium having the two exchange-coupled ferromagnetic layers with low Mrδ. Although the total thickness of the ferromagnetic layers in this case becomes greater than that of the magnetic recording medium having the single ferromagnetic layer, the read-write performance is hardly degraded, and in some cases even improved.

[0076] The present inventors have also found that, when at least one of the ferromagnetic layers of the magnetic layer structure is made up of a plurality of ferromagnetic layers which are in contact with each other and ferromagnetically coupled, a good performance is obtained especially when the lower ferromagnetic layers is Cr-rich such that the Cr content is 23 at% or greater, and the Cr content of the upper ferromagnetic layer is less. This indicates the crucial role of the lower ferromagnetic layer. According to the experiments conducted by the present inventors, it was found that the noise arising from imperfections in the lower ferromagnetic layer is effectively reduced due to cancellation from the succeeding ferromagnetic layers. In other words, it may be regarded that the lower layers form a large source of noise, but this embodiment can improve the SNR because the signals from the lower layers are cancelled such that most of the signals and thus also noise come from the upper layers.

[0077] A third embodiment of the magnetic recording medium according to the present invention is based on the above findings.

[0078] In other words, in this third embodiment, the magnetic recording medium comprises a substrate, an underlayer disposed above the substrate, and a magnetic layer structure including at least a bottom ferromagnetic layer pro-

vided on the underlayer and having a remanent magnetization and thickness product $Mr_i\delta_i$, and a top ferromagnetic layer disposed above the bottom ferromagnetic layer and having a remanent magnetization and thickness product $Mr_j\delta_j$, wherein a relationship $Mr\delta \fallingdotseq \Sigma(Mr_i\delta_i - Mr_j\delta_j)$ is satisfied, where $Mr\delta$ denotes a total remanent magnetization and thickness product of the magnetic layer structure, so that magnetization directions of adjacent ferromagnetic layers in the magnetic layer structure are closely antiparallel. δ, δ_i, and δ_j may be regarded as effective thicknesses.

[0079] The magnetic recording medium may further comprise a non-magnetic coupling layer interposed between two adjacent ferromagnetic layers of the magnetic layer structure, so that antiparallel magnetic interaction is induced thereby. This non-magnetic coupling layer may be made essentially of Ru with a thickness of approximately 0.4 to 1.0 nm. This non-magnetic coupling layer may be made of a material selected from a group of Ru, Rh, Ir, Cu, Cr and alloys thereof.

[0080] In the magnetic recording medium, each of the ferromagnetic layers of the magnetic layer structure may be made of a material selected from a group of Co, Fe, Ni, CoCrTa, CoCrPt and CoCrPt-M, where M=B, Cu, Mo, Nb, Ta, W and alloys thereof. In addition, at least one of the ferromagnetic layers of the magnetic layer structure may made up of a plurality of ferromagnetic layers which are in contact with each other and ferromagnetically coupled. The $Mr_j\delta_j$ of the top ferromagnetic layer may be largest among products of remanent magnetization and thickness of other ferromagnetic layers of the magnetic layer structure. Furthermore, the ferromagnetic layers of the magnetic layer structure may have mutually different compositions.

[0081] According to this third embodiment of the magnetic recording medium, the thermal stability and the isolated wave medium SNR Siso/Nm respectively are larger than those obtained by a magnetic recording medium with similar $Mr\delta$ but having single or multiple magnetic layers of closely parallel magnetizations. Further, the PW50 value is smaller than that obtained by a magnetic recording medium having a similar total magnetic layer thickness.

[0082] In addition, the dHc/dT value obtained in this third embodiment of the magnetic recording medium is smaller than that of the magnetic recording medium with similar $M\delta$ but having single or multiple magnetic layers of closely parallel magnetizations.

[0083] Furthermore, it was confirmed from data such as those shown in FIGS. 16 and 17 that the ferromagnetic coupling obtained in this third embodiment of the magnetic recording medium is sufficiently strong and closely antiparallel in a temperature range of approximately -10°C to 150°C.

[0084] Of course, the embodiment of the magnetic storage apparatus described above may also use one or more magnetic recording media according to the third embodiment of the magnetic recording medium described above.

[0085] Next, a description will be given of an embodiment of a recording method according to the present invention. This embodiment of the recording method uses any one of the embodiments of the magnetic recording medium described above, to magnetically record information on the magnetic recording medium in the embodiment of the magnetic storage apparatus described above.

[0086] More particularly, the method of magnetically recording information on the magnetic recording medium, comprises a step of switching magnetization direction of at least one of the ferromagnetic layers which form the magnetic layer structure of the magnetic recording medium and have antiparallel magnetization directions, as in the third embodiment of the magnetic recording medium. According to this embodiment, it is possible to make a high-density recording with improved thermal stability.

[0087] Next, a description will be given of an embodiment of a method of producing the magnetic recording medium according to the present invention.

[0088] When producing any one of the embodiments of the magnetic recording medium described above, the crystal properties and crystal orientation of the layers forming the magnetic recording medium must be appropriately controlled. The non-magnetic coupling layer in particular is extremely thin compared to the other layers such as the underlayer, and it is desirable that such a thin non-magnetic coupling layer is uniformly grown. Furthermore, in order to achieve the proper ferromagnetic coupling, the interfaces between two adjacent layers must be extremely clean and include no notable abnormalities.

[0089] Accordingly, in this embodiment of the medium producing method, the layers of the magnetic recording medium are formed sequentially (or continuously), preferably by sequential (or continuous) sputtering, since the sputtering enables an extremely thin and uniform layer to be grown as compared to other layer formation techniques. In addition, it is possible to minimize contamination between the adjacent layers by employing the sequential (or continuous) sputtering.

[0090] Furthermore, even in the case of the sputtering, it is difficult to guarantee uniform growth of a thin film having a thickness on the order of approximately 1 nm or less. Based on experiments conducted by the present inventors, the sputtering rate is preferably set to 0.35 nm/s or less in order to guarantee the uniformity of the grown thin film.

[0091] Moreover, when the gas pressure during the sputtering is too high, the layers and the interface between the adjacent layers are easily contaminated. On the other hand, when the gas pressure during the sputtering is too low, unstable plasma causes non-uniform growth of the thin film. According to experiments conducted by the present inventors, the gas pressure during the sputtering is preferably set on the order of approximately 5 mTorr.

[0092] In addition, the substrate temperature during the sputtering also needs to be optimized. A substrate temperature which is too high may cause the substrate to warp, thereby causing non-uniform growth of particularly the thin non-magnetic coupling layer. On the other hand, a substrate temperature which is too low may cause layers having unsatisfactory crystal properties to be grown. According to experiments conducted by the present inventors, the substrate temperature prior to the sputtering is set in a range of approximately 100°C to 300°C.

[0093] FIG. 20 is a diagram showing the general construction of a magnetic recording medium producing apparatus which is used in this embodiment of the medium producing method. The apparatus shown in FIG. 20 generally includes a loading and unloading unit 50, a heating chamber 51, and a plurality of sputtering chambers 52-1 through 52-n, where n depends on the layer structure of the magnetic recording medium which is produced. The last sputtering chamber 52-n connects to the loading and unloading unit 50 so as to enable unloading of the produced magnetic recording medium. For the sake of convenience, it is assumed that n=9.

[0094] First, a substrate is loaded into the loading and unloading unit 50 and heated to a substrate temperature in a range of approximately 100°C to 300°C within the heating chamber 51. Then, sequential (or continuous) DC sputtering is successively carried out in the sputtering chambers 52-1 through 52-9 to form on the substrate a NiAl layer which is 40 nm thick, a CrMo underlayer which is 20 nm thick, a CoCr intermediate layer which is 1.5 nm thick, a CoCrPtB ferromagnetic layer which is 4 nm thick, a Ru non-magnetic coupling layer which is 0.8 nm thick, a CoCrPtB ferromagnetic layer which is 4 nm thick, a Ru non-magnetic coupling layer which is 0.8 nm thick, a CoCrPtB magnetic layer, and a C protection layer.

[0095] The Ar gas pressure in the sputtering chambers 52-1 through 52-9 are set to approximately 5 mTorr. In addition, the sputtering rate is set approximately 0.35 nm/s or less and slower in the sputtering chambers 52-5 and 52-7 than in the other sputtering chambers. The slower sputtering rate can be achieved by increasing the distance between the target and the substrate by increasing the separation of the cathodes, as shown for the sputtering chamber 52-5 and 52-7.

[0096] FIG. 21 is a diagram showing the dependence of isolated wave output on effective magnetic layer thickness. In FIG. 21, the ordinate indicates the isolated wave output (μVpp), and the abscissa indicates the effective magnetic layer thickness (nm). The data shown in FIG. 21 was obtained by writing signals on the produced magnetic recording medium and reading the written signal using a GMR head. It was confirmed that the isolated wave output is proportional to the effective magnetic layer thickness, verifying the antiparallel ferromagnetic coupling of the magnetic layer structure.

[0097] FIG. 22 is a diagram showing the temperature dependence of high-frequency SNR. In FIG. 22, the ordinate indicates the high-frequency SNR (dB), and the abscissa indicates the substrate temperature (°C) during the sputtering. It was confirmed that good properties of the grown layers are obtained, preferably when the substrate temperature is set in a range of approximately 100°C to 300°C.

[0098] FIG. 23 is a diagram showing a relation ship of the isolated wave medium SNR Siso/Nm and the sputtering rate of Ru. In FIG. 23, the ordinate indicates the isolated wave medium SNR Siso/Nm (dB, relative value), and the abscissa indicates the sputtering rate (nm/s). The data shown in FIG. 23 were obtained to confirm whether or not the ferromagnetic layer and the magnetic layer respectively provided under and above the Ru layer would form a norm magnetic coupling. For the sake of convenience, the data shown in FIG. 23 were obtained for a case where the Ru layer is formed to a thickness of 1.4 nm on the CCPB ferromagnetic layer, and the CCPB magnetic layer is formed on the Ru layer.

[0099] In FIG. 23, the isolated wave medium SNR Siso/Nm is indicated by a relative value with respect to a comparison model medium having no Ru layer. It may be seen from FIG. 23 that the isolated wave medium SNR Siso/Nm deteriorates as the sputtering rate of Ru increases. This indicates that the extremely thin Ru layer is not formed uniformly at high sputtering rates. FIG. 23 indicates that the isolated wave medium SNR Siso/Nm becomes poorer than that of the comparison model medium having no Ru layer, particularly when the sputtering rate of Ru becomes greater than 0.35 nm/s. Therefore, it was confirmed that the sputtering rate of Ru should be set to 0.35 nm/s or less in order to produce a magnetic recording medium having the high performance described above.

[0100] Next, a description will be given of a fourth embodiment of the magnetic recording medium according to the present invention. In this fourth embodiment, a magnetic bonding layer is further provided at least between the ferromagnetic layer and the non-magnetic coupling layer or, between the magnetic layer and the non-magnetic coupling layer of the first or second embodiment described above. In this fourth embodiment, the magnetic bonding layer is additionally provided to increase the exchange coupling effect, so as to further improve the thermal stability.

[0101] FIG. 24 is a cross sectional view showing an important part of the fourth embodiment of the magnetic recording medium according to the present invention.

[0102] The magnetic recording medium includes a non-magnetic substrate 101, a seed layer 102, an underlayer 103, a non-magnetic intermediate layer 104, a ferromagnetic layer 105, a lower magnetic bonding layer 106, a non-magnetic coupling layer 107, an upper magnetic bonding layer 108, a magnetic layer 109, a protection layer 110, and a lubricant layer 111 which are stacked in this order as shown in FIG. 24.

[0103] Although two magnetic bonding layers are provided in this embodiment, it is possible to provide only one of the upper and lower magnetic bonding layers 108 and 106. When both the upper and lower magnetic bonding layers 108 and 106 are provided, the exchange coupling effects of the upper and lower magnetic bonding layers 108 and 106 are set so as to be greater than the exchange coupling effects of the magnetic layer 109 and the ferromagnetic layer 105. By setting the exchange coupling effects of the upper and lower magnetic bonding layers 108 and 106 in this manner, the exchange coupling strength is increased above and below the non-magnetic coupling layer 107, so that the thermal stability of the magnetic recording medium is improved.

[0104] If only one magnetic bonding layer is provided, the exchange coupling strength is increased between the lower magnetic bonding layer 106 and the magnetic layer 109 or, between the upper magnetic bonding layer 108 and the ferromagnetic layer 105, thereby improving the thermal stability of the magnetic recording medium.

[0105] For example, the non-magnetic substrate 101 is made of Al, Al alloy or glass. The non-magnetic substrate 101 may or may not be mechanically textured.

[0106] The seed layer 102 is made of NiP, for example, especially in the case where the non-magnetic substrate 101 is made of Al or Al alloy. The NiP seed layer 102 may or may not be oxidized and may or may not be mechanically textured. Especially in the case where the non-magnetic substrate 101 is made of glass, the seed layer 102 is made of an alloy having the B2 structure and selected from a group of materials including NiAl and FeAl, for example. The seed layer 102 is provided to promote a (001) or a (112) texture of the underlayer 103.

[0107] In a case where the magnetic recording medium is a magnetic disk, the mechanical texturing provided on the non-magnetic substrate 101 or the NiP seed layer 102 is made in a circumferential direction of the disk, that is, in a direction in which tracks of the disk extend.

[0108] The non-magnetic intermediate layer 104 is provided to further promote epitaxy, narrow the grain distribution width of the magnetic layer 109, and orient the anisotropy axes of the magnetic layer 109 along a plane parallel to the recording surface of the magnetic recording medium. This non-magnetic intermediate layer 104 is made of a hcp structure alloy such as CoCr-M, where M = B, Mo, Nb, Ta, W, Cu or alloys thereof, and has a thickness in a range of 1 to 5 nm.

[0109] The ferromagnetic layer 105 is made of Co, Ni, Fe, Co-based alloys, Ni-based alloys, Fe-based alloys or the like. In other words, Co-based alloys such as CoCrTa, CoCrPt and CoCrPt-M, where M = B, Mo, Nb, Ta, W, Cu or alloys thereof may be used for the ferromagnetic layer 105. For example, the ferromagnetic layer 105 has a thickness in a range of approximately 2 to 10 nm.

[0110] The lower magnetic bonding layer 106 is made of Co, Fe, Ni-based alloys, Co-based alloys, Fe-based alloys or the like. In other words, Co-based alloys such as CoCrTa, CoCrPt and CoCrPt-M may be used for the lower magnetic bonding layer 106, where M = B, Mo, Nb, Ta, W, Cu or alloys thereof. The Co concentration or Fe concentration of the lower magnetic bonding layer 106 is desirably higher than the Co concentration or Fe concentration of the ferromagnetic layer 105. The lower magnetic bonding layer 106 has a thickness in a range of approximately 1 to 5 nm.

[0111] In a case where Co or Fe is used for the ferromagnetic layer 105, it is possible to omit the lower magnetic bonding layer 106. On the other hand, when providing the lower magnetic bonding layer 106, Fe or Co is used in reverse to the ferromagnetic layer 105.

[0112] In other words, the Co or Fe concentration of the lower magnetic bonding layer 106 (and the upper magnetic bonding layer 108 which will be described later) is preferably higher than the Co or Fe concentrations of the ferromagnetic layer 105 and the magnetic layer 109. If Co or Fe is used for the ferromagnetic layer 105 or the magnetic layer 109, the lower magnetic bonding layer 106 may be omitted. When providing the magnetic bonding layer 106, the material used for the magnetic bonding layer 106 is preferably in reverse to that used for the ferromagnetic layer 105 or the magnetic layer 109, that is, Fe or Co is used for the magnetic bonding layer 106.

[0113] The non-magnetic coupling layer 107 is made of Ru, Rh, Ir, Cr, Cu, Ru-based alloys, Rh-based alloys, Ir-based alloys, Cr-based alloys, Cu-based alloys or the like.

[0114] When Ru, Rh, Ir, Cu, Ru-based alloys, Rh-based alloys, Ir-based alloys or Cu-based alloys are used for the non-magnetic coupling layer 107, Co, Co-based alloys or NiFe is desirably used for the magnetic bonding layer 106. In addition, the magnetic bonding layer 106 is desirably made of Fe or Fe-based alloys when the non-magnetic coupling layer 107 is made of Cr or Cr-based alloys.

[0115] For example, when the non-magnetic coupling layer 107 is made of Ru, the thickness of the non-magnetic coupling layer 107 is set in a range of approximately 0.4 to 1.0 nm, and preferably to approximately 0.8 nm. By setting the thickness of the non-magnetic coupling layer 107 to such a range, the magnetizations of the ferromagnetic layer 105 and the magnetic layer 109 become antiparallel.

[0116] In other words, the magnetization directions of the ferromagnetic layer 105 and the magnetic layer 109 may be mutually antiparallel or mutually parallel.

[0117] In the case of the mutually antiparallel magnetization directions, the non-magnetic coupling layer 107 desirably has a thickness in a range of approximately 0.4 to 1.0 nm when made of a material selected from a group of Ru, Rh, Ir, Cr, Ru-based alloys, Rh-based alloys, Ir-based alloys and Cr-based alloys, and has a thickness in a range of approximately 1.5 to 2.1 nm when made of a material selected from a group of Cu and Cu-based alloys.

[0118] On the other hand, in the case of mutually parallel magnetization directions, the non-magnetic coupling layer 107 desirably has a thickness in a range of approximately 0.2 to 0.4 nm and 1.0 to 1.7 nm when made of a material selected from a group of Ru, Rh, Ir, Cu, Ru-based alloys, Rh-based alloys, Ir-based alloys and Cu-based alloys, and has a thickness in a range of approximately 1.0 to 1.4 nm and 2.6 to 3.0 nm when made of a material selected from a group of Cr and Cr-based alloys.

[0119] The upper magnetic bonding layer 108 is made of a material similar to that of the lower magnetic bonding layer 106. In addition, the Co concentration or Fe concentration of the upper magnetic bonding layer 108 is preferably higher than the Co concentration or Fe concentration of the magnetic layer 109. The upper magnetic bonding layer 108 has a thickness in a range of approximately 1 to 5 nm. In a case where Co or Fe is used for the magnetic layer 109, it is possible to omit the upper magnetic bonding layer 108. On the other hand, when providing the upper magnetic bonding layer 108, Fe or Co is used in reverse to the magnetic layer 109.

[0120] The upper and lower magnetic bonding layers 108 and 106 may be made of a material different from those of the ferromagnetic layer 105 and the magnetic layer 109. In this case, a different material may have the same material composition but with a different material content ratio.

[0121] The exchange coupling between the upper and lower magnetic bonding layers 108 and 106 is desirably larger than the exchange coupling between the magnetic layer 109 and the ferromagnetic layer 105.

[0122] When using Ru, Rh, Ir, Cu, Ru-based alloys, Rh-based alloys, Ir-based alloys or Cu-based alloys for the non-magnetic coupling layer 107, it is desirable to use Co, Co-based alloys or NiFe for the upper and lower magnetic bonding layers 108 and 106. On the other hand, when using Cr or Cr-based alloys for the non-magnetic coupling layer 107, it is desirable to use Fe or Fe-based alloys for the upper and lower magnetic bonding layers 108 and 106.

[0123] The ferromagnetic layer 105 and the non-magnetic coupling layer 107 form the basic exchange layer structure. The upper and lower magnetic bonding layers 108 and 106 which are provided above and below the non-magnetic coupling layer 107 have the function of increasing the exchange coupling effects of the exchange layer structure.

[0124] The magnetic layer 109 is made of a material selected from a group of Co, Ni, Fe, Ni-based alloys, Fe-based alloys and Co-based alloys such as CoCrTa, CoCrPt and CoCrPt-M, where M = B, Mo, Nb, Ta, W, Cu or alloys thereof. The magnetic layer 109 has a thickness in a range of 5 to 30 nm. Of course, the magnetic layer 109 is not limited to a single-layer structure, and a multi-layer structure may be used for the magnetic layer 109.

[0125] The protection layer 110 and the lubricant layer 111 are similar to those of the first and second embodiments described above. Obviously, the layer structure under the exchange layer structure is not limited to that shown in FIG. 24. For example, the underlayer 103 may be made of Cr or Cr-based alloys and formed to a thickness in a range of 5 to 40 nm on the substrate 101, and the exchange layer structure may be provided on this underlayer 103.

[0126] In this fourth embodiment, the magnetic recording medium may further comprise a substrate and an underlayer provided above the substrate, such that the exchange layer structure is provided above the underlayer. Furthermore, the magnetic recording medium may further comprise a non-magnetic intermediate layer provided between the underlayer and the exchange layer structure, where the non-magnetic intermediate layer is made of a CoCr-M alloy having a hcp structure and a thickness of approximately 1 to 5 nm, where M = B, Mo, Nb, Ta, W, Cu or alloys thereof. Moreover, the magnetic recording medium may further comprise a seed layer provided between the substrate and the underlayer. The seed layer may be made of NiP which may or may not be mechanically textured, and may or may not be oxidized. In addition, the seed layer may be made of an alloy having a B2 structure such as NiAl and FeAl.

[0127] The magnetic recording medium may further comprise at least a first exchange layer structure and a second exchange layer structure provided between the first exchange layer structure and the magnetic layer, where the second exchange layer structure has a ferromagnetic layer with a magnetic anisotropy smaller than that of a ferromagnetic layer of the first exchange layer structure, and the first and second exchange layer structures have ferromagnetic layers with magnetization directions which are mutually antiparallel.

[0128] The magnetic recording medium may further comprise at least a first exchange layer structure and a second exchange layer structure provided between the first exchange layer structure and the magnetic layer, where the second exchange layer structure has a ferromagnetic layer with a remanent magnetization and thickness product smaller than that of a ferromagnetic layer of the first exchange layer structure, and the first and second exchange layer structures have ferromagnetic layers with magnetization directions which are mutually antiparallel.

[0129] FIG. 25 is a diagram showing the in-plane characteristic of two CoCr-based alloy layers separated by Ru, for a case where a seed layer, an underlayer, a non-magnetic intermediate layer, a ferromagnetic layer, a Ru non-magnetic coupling layer, a CoCr-based alloy magnetic layer are successively stacked in this order on a glass substrate.

[0130] It is assumed that the same CoCr-based alloy is used for the ferromagnetic layer and the magnetic layer. In FIG. 25, two loops are shown for different concentrations of Co and Cr, but the layer structure and compositions other than Co and Cr are the same for the two loops. In FIG. 25, the ordinate indicates the magnetization (emu/cc), and the abscissa indicates the magnetic field (Oe).

[0131] As may be seen from FIG. 25, a shift occurs in both the two loops in the vicinity of the ordinate, verifying the generation of the anti-ferromagnetic coupling. Furthermore, it may be seen from FIG. 25 that the loop indicated by the

dashed line for the higher concentration of Co (Co-rich) has the larger coercivity. Even in the case of the conventional magnetic recording medium having no exchange layer structure, the coercivity is improved by approximately 400 Oe for the magnetic layer with the high Co concentration as compared to the magnetic layer with the low Co concentration. Since the loop shift occurs when a sum of the externally applied magnetic field and the magnetic field caused by the anti-ferromagnetic coupling introduced between the magnetic layer and the ferromagnetic layer becomes equal to the coercivity, a difference between the loop shift position and the coercivity becomes the strength of the anti-ferromagnetic exchange coupling. In FIG. 25, the loop shifts occur approximately at the same magnetic field position, but it may be seen that the exchange coupling is larger for the Co-rich case indicated by the dashed line due to a difference in coercivities between the two cases. In addition, the aspect ratio of the Co-rich loop is better than the other loop.

[0132] Therefore, by using a Co-rich alloy for the magnetic bonding layer, it is possible to increase the exchange coupling effect and realize a magnetic recording medium having a further improved thermal stability.

[0133] In the magnetic recording medium having the exchange layer structure such as that of the first embodiment shown in FIG. 1, when Ru is used for the non-magnetic coupling layer 8 and a CoCr-based alloy is used for the magnetic layer 9, both of these layers 8 and 9 have the hcp structure. In order to increase both the coercivity and resolution of the magnetic recording medium, it is desirable that the c-axis of the hcp structure is parallel with respect to the surface of the substrate 1. In a case where a CoCr-based alloy is used for the ferromagnetic layer 7, the ferromagnetic layer 7 is grown epitaxially on the non-magnetic intermediate layer 6 which is made of an alloy having the hcp structure and oriented on the (002) face, and thus, the in-plane orientation of the c-axis of the ferromagnetic layer 7 is very satisfactory.

[0134] On the other hand, the Ru which is used for the non-magnetic coupling layer 8 has the hcp structure, similarly as in the case of the CoCr-based alloy, but the lattice constant of Ru is approximately 5% larger than the lattice constant of the CoCr-based alloy. For this reason, the epitaxial growth may be slightly obstructed due to the lattice mismatch between the ferromagnetic layer 7 and the non-magnetic coupling layer 8 or, between the non-magnetic coupling layer 8 and the magnetic layer 9. If the epitaxial growth is slightly obstructed due to the lattice mismatch, the coercivity of the magnetic recording medium decreases, and the in-plane orientation of the c-axis of the CoCr-based alloy becomes unstable.

[0135] Next, a description will be given of an embodiment which can improve the epitaxial growth between the Ru and the CoCr-based alloy, simultaneously increase the coercivity of the magnetic recording medium and improve the in-plane orientation of the c-axis of the CoCr-based alloy, and improve mainly the recording resolution characteristic of the magnetic recording medium.

[0136] FIG. 26 is a cross sectional view showing an important part of a fifth embodiment of the magnetic recording medium according to the present invention.

[0137] The magnetic recording medium includes a non-magnetic substrate 216, a seed layer 217, an underlayer 218 made of a Cr-based alloy, a non-magnetic intermediate layer 219, a ferromagnetic layer 220, a non-magnetic coupling layer 221, a magnetic layer 222, a protection layer 223, and a lubricant layer 224 which are stacked in this order as shown in FIG. 26.

[0138] The non-magnetic substrate 216 is made of an Al alloy or glass, for example. The non-magnetic substrate 216 may or may not be mechanically textured. The seed layer 217 is made of NiP which is plated in a case where the non-magnetic substrate 216 is made of the Al alloy. The NiP seed layer 217 may or may not be mechanically textured. On the other hand, in a case where the non-magnetic substrate 216 is made of glass, the seed layer 217 is made of an intermetallic compound material having the B2 structure, such as NiAl and FeAl.

[0139] The non-magnetic intermediate layer 219 is provided to promote the epitaxial growth of the magnetic layer 222, reduction of the grain size distribution with of the magnetic layer 222, and the anisotropic axis (c-axis, axis of easy magnetization) orientation of the magnetic layer 222 along a plane parallel to the recording surface of the magnetic recording medium. The non-magnetic intermediate layer 219 is made of an alloy having the hcp structure, such as CoCr-M1, and has a thickness in a range of approximately 1 to 5 nm, where M1 = B, Mo, Bn, Ta, W or alloys thereof.

[0140] The ferromagnetic layer 220 is made of a material selected from a group of Co, Ni, Fe, Co-based alloys, Ni-based alloys, Fe-based alloys and the like. In other words, Co-based alloys including CoCrTa, CoCrPt and CoCrPt-M2 may be used for the ferromagnetic layer 220, where M2 = B, Mo, Nb, Ta, W or alloys thereof. The ferromagnetic layer 220 has a thickness in a range of approximately 2 to 10 nm.

[0141] The non-magnetic coupling layer 221 is made of an alloy having the hcp structure, such as Ru-M3, where M3 = Co, Cr, Fe, Ni, Mn or alloys thereof. For example, the non-magnetic coupling layer 221 has a thickness in a range of approximately 0.4 to 1.0 nm, and preferably in a range of approximately 0.6 to 0.8 nm. By setting the thickness of the non-magnetic coupling layer 221 within such a range, the magnetizations of the ferromagnetic layer 220 and the magnetic layer 222 become antiparallel. Accordingly, the ferromagnetic layer 220 and the non-magnetic coupling layer 219 form an exchange layer structure.

[0142] The magnetic layer 222 is made of a material selected from a group of Co and Co-based alloys including CoCrTa, CoCrPt, and CoCrPt-M4, where M4 = B, Mo, Nb, Ta, W or alloys thereof. The magnetic layer 222 has a thick-

ness in a range of approximately 5 to 30 nm. Of course, the magnetic layer 222 is not limited to a single-layer structure, and a multi-layer structure may be used for the magnetic layer 222.

[0143] The protection layer 223 is made of C or diamond-like C (DLC). In addition, the lubricant layer 224 is made of an organic lubricant agent, in order to enable the magnetic recording medium to be used with a magnetic transducer such as a spin valve head. The protection layer 223 and the lubricant layer 224 form a protection layer structure of the magnetic recording medium.

[0144] As described above, the non-magnetic coupling layer 221 is made of an alloy Ru-M3, where M3 = Co, Cr, Fe, Ni, Mn or alloys thereof. In this embodiment, an amount of the element M3 added to the Ru is set within the following composition ranges so as to maintain a stable hcp structure. In the following composition ranges, the numerical values following the brackets respectively indicate the amount in atomic percent (at%).

Ru-Co(0 to 50 at%)
Ru-Cr(0 to 50 at%)
Ru-Fe(0 to 60 at%)
Ru-Ni(0 to 10 at%)
Ru-Mn(0 to 50 at%)

[0145] FIG. 27 is a diagram showing a magnetization curve which is obtained when pure Ru is used for the non-magnetic coupling layer 221 of the magnetic recording medium shown in FIG. 26. In FIG. 27, the ordinate indicates the magnetization M (arbitrary units), and the abscissa indicates the magnetic field H (kOe). The magnetization curve shown in FIG. 27 was measured by a vibrating sample type magnetometer while applying a magnetic field parallel to the sample surface, that is, parallel to the recording surface of the magnetic recording medium. The magnetization curve has a constricted portion because of the existence of a region where the ferromagnetic layer 220 and the magnetic layer 222 form an antiparallel coupling.

[0146] In addition, a magnetization curve which is obtained when a Ru-M3 alloy is used for the non-magnetic coupling layer 221 was also measured similarly to the above. In the case where the Ru-M3 alloy is used for the non-magnetic coupling layer 221, it was also confirmed that a constricted portion is formed in the magnetization curve, similarly as in the case shown in FIG. 27, due to the existence of the region where the ferromagnetic layer 220 and the magnetic layer 222 form the antiparallel coupling.

[0147] In the first and fourth quadrants in FIG. 27, a linear portion of the magnetization curve on the higher magnetic field side of the constricted portion is extrapolated to the magnetic field axis, and the intersection with the magnetic field axis is defined as an in-plane coercivity Hc//.

[0148] FIG. 28 is a diagram showing a magnetization curve which is measured by a vertical Kerr looper (or loop) while applying a magnetic field in a perpendicular direction with respect to the sample surface, with respect to the magnetic recording medium for which the data shown in FIG. 27 were measured. In FIG. 28, the ordinate indicates the Kerr rotation (degrees), and the abscissa indicates the perpendicular magnetic field (Oe). A definition of a perpendicular coercivity Hc⊥ is shown in FIG. 28.

[0149] The extent of the in-plane orientation of the axis of easy magnetization of the magnetic layer 222 can be evaluated by a ratio (Hc⊥)/(Hc//). The smaller this ratio (Hc⊥)/(Hc//), the better the in-plane orientation of the magnetic layer 222.

[0150] Measured results of the in-plane coercivity Hc// and the ratio (Hc⊥)/(Hc//) for various materials used for the non-magnetic coupling layer 221 are shown in the following. In the following, the in-plane coercivity Hc// of the various materials is indicated by a relative value relative to the in-plane coercivity Hc// = 1 for the case where pure Ru is used for the non-magnetic coupling layer 221.

Non-Magnetic Coupling Layer 221	Hc// (Relative Value)	(Hc⊥)/(Hc//)
Ru	1	0.33
Ru-Co(20at%)	1.10	0.23
Ru-Cr(20at%)	1.05	0.25
Ru-Fe(20at%)	1.07	0.28
Ru-Mn(20at%)	0.96	0.30
Ru-Ni(10at%)	0.94	0.30

[0151] Therefore, it was confirmed that the ratios (Hc⊥)/(Hc//) for the cases where the Ru-M3 alloys are used for the non-magnetic coupling layer 221 are improved according to this embodiment, as compared to the case where pure Ru is used for the non-magnetic coupling layer 221. As a result, it was confirmed that the recording resolution is improved by approximately 1.5 to 2.5 % by the improved in-plane orientation of the magnetic layer 222.

[0152] A lattice mismatch of the intervals of the (002) faces of the hcp structure of the Ru used for the non-magnetic coupling layer 221 with respect to the magnetic layer 222 and the ferromagnetic layer 220 respectively disposed above and below the non-magnetic coupling layer 221 is normally approximately 5 % at the maximum and approximately 8 % in a worst case. But by the addition of the element M3 to the Ru, it was confirmed that the lattice mismatch can be reduced to approximately 6 % or less, and preferably approximately 2 % or less. Furthermore, the element M3 added to the Ru is preferably Co, Cr, Fe, Ni, Mn or alloys thereof, but it is of course possible to adjust the lattice mismatch by adding to the Ru a material selected from a group of Ir, Mo, Nb, Pt, Rh, Ta, Ti, V, W and alloys thereof.

[0153] Of course, this embodiment may be applied similarly to the construction of the second embodiment of the magnetic recording medium described above.

[0154] Next, the prior art will be briefly summarized before explaining further features of the present invention in conjunction with FIGS. 29 through 32.

[0155] Due to the development of the information processing technology, there are increased demands for high-density magnetic recording media. Characteristics required of the magnetic recording media to satisfy such demands include low noise, high coercivity, high remanence magnetization, and high resolution.

[0156] Conventionally, various measures have been proposed to reduce the noise in the magnetic recording media. A general magnetic recording medium basically includes a non-magnetic substrate made of Al or the like, and an underlayer, a magnetic recording layer, a protection layer and a lubricant layer which are stacked in this order on the substrate. For example, with respect to the underlayer, functions such as promoting the in-plane orientation of the magnetic recording layer and increasing the remanence magnetization and thermal stability of written bits are demanded, in order to improve the magnetization characteristic of the magnetic recording layer. When a suitable underlayer is used, it is possible to reduce the thickness of the magnetic recording layer or, to reduce the size of the magnetic grains and the grain size distribution width of the magnetic recording layer, thereby enabling noise reduction.

[0157] In addition, there are proposals to increase the resolution by reducing the thickness of the magnetic layer or, to reduce the transition width between the written bits. There are also proposals to promote the Cr segregation of the CoCr-based alloy which forms the magnetic recording layer, so as to reduce the exchange coupling among the magnetic grains. These proposals have been made to reduce noise from various aspects.

[0158] As one technique which is effective in reducing noise, there is a proposal to employ a multi-layer structure for the magnetic recording layer, by separating the magnetic recording layer into upper and lower portions by a separation layer. By employing the multi-layer structure with the separation layer for the magnetic recording layer, it is possible to separate the magnetic coupling of the magnetic layers, and to positively reduce the noise.

[0159] However, in the magnetic recording layer having the multi-layer structure, a non-magnetic material such as CoCr-based alloys and Cr-based alloys are used for the separation layer. However, such non-magnetic materials easily mix with the magnetic layers which are provide above and below, thereby deteriorating the magnetic characteristics of the magnetic recording layer, and there was a problem in that the reproduced output obtained from such a magnetic recording medium is deteriorated thereby. Furthermore, the non-magnetic materials such as the CoCr-based alloys and Cr-based alloys virtually separate completely the magnetic coupling of the magnetic layers provided above and below. Hence, although such non-magnetic materials are preferable from the point of reducing the noise, the magnetic layers provided above and below become thermally unstable as a result. Consequently, in the case of a magnetic recording medium such as a magnetic disk which may be used under a relatively high temperature environment, there was a problem in that the detection sensitivity of written bits deteriorates due to the provision of such a separation layer.

[0160] Next, a description will be given of a sixth embodiment of the magnetic recording medium according to the present invention, which has a magnetic recording layer with a multi-layer structure, wherein the noise can be reduced while maintaining the desired thermal stability and magnetic characteristics.

[0161] In the first and second embodiments, a magnetic recording medium comprising at least one exchange layer structure, and a magnetic layer provided on the exchange layer structure, wherein the exchange layer structure includes a ferromagnetic layer and a non-magnetic coupling layer provided on the ferromagnetic layer and under the magnetic layer, and the magnetization directions of the ferromagnetic layer and the magnetic layer are mutually antiparallel.

[0162] In the first and second embodiments, for a particular Ru or Ir layer thickness between two ferromagnetic layers, the magnetizations can be made parallel or antiparallel. For example, for a structure made up of two ferromagnetic layers of different thickness with antiparallel magnetizations, the effective grain size of a magnetic recording medium can be increased without significantly affecting the resolution. A signal amplitude reproduced from such a magnetic recording medium is reduced due to the opposite magnetizations, but this can be rectified by adding another layer of appropriate thickness and magnetization direction, under the laminated magnetic layer structure, to thereby cancel the effect of one of the layers. As a result, it is possible to increase the signal amplitude reproduced from the magnetic

recording medium, and to also increase the effective grain volume. Thermally stable written bits can therefore be realized.

[0163] The first and second embodiments increase the thermal stability of written bits by exchange coupling the magnetic layer to another ferromagnetic layer with an opposite magnetization or, by a laminated ferrimagnetic structure. The ferromagnetic layer or the laminated ferrimagnetic structure is made up of exchange-decoupled grains as the magnetic layer. In other words, the first and second embodiments use an exchange pinning ferromagnetic layer or a ferrimagnetic multilayer to improve the thermal stability performance of the magnetic recording medium.

[0164] In the sixth embodiment described hereunder, the above findings associated with the first and second embodiments are effectively utilized, by noting that the magnetization directions of the two ferromagnetic layers become mutually parallel when the layer made of Ru or the like provided between the two ferromagnetic layer has a specific thickness. Accordingly, the sixth embodiment also employs a layer structure similar to the basic layer structure of the first and second embodiments. The magnetic layer, the non-magnetic coupling layer and the ferromagnetic layer of the first and second embodiments respectively correspond to the (first) magnetic recording layer, the non-magnetic separation layer and the (second) magnetic recording layer of the sixth embodiment, but the functions of the layers of the sixth embodiment differ from those of the first and second embodiments.

[0165] The basic structure of the sixth embodiment of the magnetic recording medium according to the present invention includes a non-magnetic substrate, an underlayer, a magnetic recording layer, a protection layer and a lubricant layer which are stacked in this order, similarly to the conventional magnetic recording medium, but the magnetic recording layer has a multi-layer structure.

[0166] FIG. 29 is a cross sectional view showing an important part of the sixth embodiment of the magnetic recording medium according to the present invention. A magnetic recording medium 30 includes a non-magnetic substrate 31, a NiP layer 32, an underlayer 33, a non-magnetic intermediate layer 34, a second magnetic recording layer 35, a non-magnetic separation layer 36, a first magnetic recording layer 37, a protection layer 38, and a lubricant layer 39 which are stacked in this order as shown in FIG. 29.

[0167] A magnetic recording layer of this magnetic recording medium 30 has a 3-layer structure, including the second magnetic recording layer 35, the non-magnetic separation layer 36 and the first magnetic recording layer 37. As will be described later, the upper first magnetic recording layer 37 and the lower second magnetic recording layer 35 are magnetically coupled via the non-magnetic separation layer 36, and magnetization directions of the first and second magnetic recording layers 37 and 35 are parallel (in the same direction). When the magnetic recording medium 30 is formed as a magnetic disk and signals are recorded thereon by a magnetic head, the first and second magnetic recording layers 37 and 35 which are in the above described relationship are fixed along the recording magnetization while maintaining the mutually parallel state. The magnetization states of the first and second magnetic recording layers 37 and 35 are read at the time of the signal reproduction.

[0168] Because the first and second magnetic recording layers 37 and 35 are separated by the non-magnetic separation layer 36, low noise is realized by the effects of magnetic separation. However, unlike the conventional non-magnetic separation layer made of CoCr-based alloys or Cr-based alloys, a magnetic coupling which is sufficient to maintain the mutually parallel magnetization states of the first and second magnetic recording layers 37 and 35 exists in the case of this embodiment. As a result, the thermal stability is improved, and the reliability of the magnetic recording medium 30 is improved over the conventional magnetic medium since the magnetic characteristics desired of the magnetic recording layer can be maintained in this embodiment even under a relatively high temperature environment.

[0169] In the magnetic recording layer having the multi-layer structure, two or more non-magnetic separation layers may be provided. For example, when providing two non-magnetic separation layers, the magnetic recording layer is formed by first, second and third magnetic recording layers, and a first non-magnetic separation layer is interposed between the first and second magnetic recording layers, while a second non-magnetic separation layer is interposed between the second and third magnetic recording layers.

[0170] Returning now to the description of the magnetic recording medium 30 shown in FIG. 29, the non-magnetic substrate 31 is made of a non-magnetic material such as Al, Al alloy and glass. The non-magnetic substrate 31 may or may not be mechanically textured.

[0171] The NiP layer 32 is made of NiP, but may be replaced by a layer made of a material such as NiAl and FeAl having the B2 structure. The NiP layer 32 may or may not be mechanically textured. In the case where the magnetic recording medium 30 is a magnetic disk and the mechanical texturing is to be made, the non-magnetic substrate 31 and the NiP layer 32 are mechanically textured in the circumferential direction of the magnetic disk, that is, in a direction in which a track on the magnetic disk is formed.

[0172] The underlayer 33 is made of at least one layer of a Cr-based alloy. For example, the underlayer 33 may be made of a Cr-M alloy, where M = Mo, Fe, Mn, Ti, V, W or alloys thereof.

[0173] The non-magnetic intermediate layer 34 is provided to promote the epitaxial growth of the first and second magnetic recording layers 37 and 35, reduction of the grain size distribution width, and orientation of the anisotropy axes (axis of easy magnetization) of the magnetic recording layer in a plane parallel to the recording surface of the mag-

netic recording medium 30. The non-magnetic intermediate layer 34 is made of a CoCr-M alloy having the hcp structure, where M = B, Mn, Mo, Nb, Ta, Ti, W or alloys thereof, and has a thickness in a range of approximately 1 to 5 nm. It is not essential to provide the non-magnetic intermediate layer 34, and it is possible to omit the non-magnetic intermediate layer 34.

[0174] The second magnetic recording layer 35 is made of a material such as Co, Ni, Fe, Co-based alloys, Ni-based alloys and Fe-based alloys, In other words, Co and Co-based alloys including CoCrTa, CoCrPt and CoCrPt-M may be used for the second magnetic recording layer 35, where M = B, Mo, Nb, Ta, W or alloys thereof. Preferably, the second magnetic recording layer 35 has a thickness in a range of approximately 2 to 10 nm.

[0175] The non-magnetic separation layer 36 is made of a material such as Ru, Rh, Ir and alloys thereof. When using Ru for the non-magnetic separation layer 36, the thickness of the non-magnetic separation layer 36 is preferably set in a range of approximately 0.2 to 0.4 nm or approximately 1.0 to 1.7 nm. By setting the thickness of the non-magnetic separation layer 36 to such a range, it is possible to set the magnetization directions of the second magnetic recording layer 35 and the first magnetic recording layer 37 to become mutually parallel.

[0176] The first magnetic recording layer 37 may be made of a material such as Co, and Co-based alloys including CoCrTa, CoCrPt and CoCrPt-M, similarly to the second magnetic recording layer 35, where M = B, Mo, Nb, Ta, W or alloys thereof. Preferably, the first magnetic recording layer 37 has a thickness in a range of approximately 5 to 30 nm. The first magnetic recording layer 37 is not limited to a single-layer structure, and the first magnetic recording layer 37 itself may have a multi-layer structure.

[0177] The materials forming the first and second magnetic recording layers 37 and 35 may be the same or, may be mutually different.

[0178] The protection layer 38 is made of a C-based material, for example. In addition, the lubricant layer 39 is made of an organic lubricant agent to enable use of the magnetic recording medium 30 with a magnetic transducer such as a spin valve head. The protection layer 38 and the lubricant layer 39 form a protection layer structure of the magnetic recording medium 30.

[0179] The layer structure of sixth embodiment of the magnetic recording medium according to the present invention is of course not limited to that shown in FIG. 29. For example, the underlayer 33 may be made of Cr or a Cr-based alloy, and formed to a thickness in a range of approximately 5 to 40 nm. The second magnetic recording layer 35 may be provided on such an underlayer 33.

[0180] Next, a description will be given of a method of producing the magnetic recording medium 30. The layers formed on the substrate 31 of the magnetic recording medium 30, from the underlayer 33 up to the protection layer 38, may be formed by sputtering.

[0181] For example, after cleaning the NiP-plated Al substrate 31 which has a thickness of 0.8 mm and a diameter of 3.5 inches, a magnetron sputtering apparatus is used to heat the Al substrate 31 to a substrate temperature of 220°C, and the layers from the underlayer 33 up to the protection layer 38 are successively formed by sputtering. The NiP layer on the Al substrate 31 may be oxidized or mechanically textured. The sputtering is carried out at a pressure of 5 mTorr and a constant sputtering time of 4 seconds. The underlayer 33 is formed to a thickness of 10 nm by sputtering a material $Cr_{95}Mo_{2.5}W_{2.5}$ to a thickness of 3 nm, and sputtering a material $Cr_{80}Mo_{10}W_{10}$ to a thickness of 7 nm. The non-magnetic intermediate layer 34 is formed to a thickness of 3 nm by sputtering a material $Co_{63}Cr_{37}$. The second magnetic recording layer 35 is formed to a thickness of 9.5 nm by sputtering a material $Co_{63}Cr_{22}Pt_{11}B_4$. The non-magnetic separation layer 36 is formed to a thickness selected within a range of 0.2 to 0.4 nm or 1.0 to 1.7 nm by sputtering Ru. The first magnetic recording layer 37 is formed to a thickness of 9.5 nm by sputtering a material $Co_{63}Cr_{22}Pt_{11}B_4$. Furthermore, the protection layer 38 is formed by sputtering a C-based material, and the lubricant layer 39 is formed by coating an organic lubricant agent on the protection layer 38.

[0182] FIG. 30 is a diagram showing the relationship of a ratio Siso/Nm of the isolated wave output (Siso) and medium noise (Nm) of this embodiment of the magnetic recording medium 30 which is produced as described above and the thickness of the Ru non-magnetic separation layer 36. The ratio Siso/Nm is a ratio of the isolated wave output Siso at 270 kFCI and the medium noise Mm. It was confirmed from FIG. 30 that the noise is reduced, since the value of the ratio Siso/Nm increases as the thickness of the non-magnetic separation layer 36 increases.

[0183] As described above, when Ru is used for the non-magnetic separation layer 36, the magnetization directions of the first and second magnetic layers 37 and 35 disposed above and below the non-magnetic separation layer 36 become mutually parallel or mutually antiparallel depending on the thickness of the non-magnetic separation layer 36. In this embodiment, the magnetizations of the first and second magnetic recording layers 37 and 35 becomes mutually parallel by setting the thickness of the non-magnetic separation layer 36 to approximately 0.4 nm or less or approximately 1.0 nm or greater.

[0184] FIG. 31 is a diagram showing the relationship of a thickness ratio of first and second magnetic recording layers 37 and 35 and the ratio Siso/Nm of the isolated wave output (Siso) and medium noise (Nm), for a case where the same material $CO_{63}Cr_{22}Pt_{11}B_4$ is used for the first and second magnetic recording layers 37 and 35. In FIG. 31, the abscissa indicates a thickness ratio (thickness of the first magnetic recording layer 37)/{(thickness of the first magnetic

recording layer 37)+(thickness of the second magnetic recording layer 35)}. It was confirmed from FIG. 31 that a high ratio Siso/Nm can be obtained when the thickness ratio is in a range of approximately 0.5 to 0.7.

[0185] FIG. 32 is a diagram showing the relationship of the thickness ratio of the first and second magnetic recording layers 37 and 35 and a ratio S/Nt of an output (S) and noise (Nt). In FIG. 32, the abscissa is the same as that of FIG. 11. It was confirmed from FIG. 32 that a high ratio S/Nt can also be obtained when the thickness ratio is in a range of approximately 0.5 to 0.7.

[0186] From FIGS. 31 and 32, it was confirmed that the noise reducing effect is further improved when a thickness ratio of the thickness of the first magnetic recording layer 37 to the thickness of the second magnetic recording layer 35 is in a range of approximately 5:5 to 7:3. The thickness ratio is desirably set close to 5:5 from the point of view of realizing low noise, and is desirably set close to 7:3 from the point of view of realizing high resolution.

[0187] Therefore, according to the sixth embodiment of the magnetic recording medium, a non-magnetic separation layer which is made of Ru or the like and has a predetermined thickness maintains the magnetic coupling of magnetic recording layers above and below the non-magnetic separation layer to a mutually parallel state. Hence, it is possible to realize a magnetic recording medium having low noise and desired thermal stability. Compared to the conventional magnetic recording medium, this magnetic recording medium has a high reliability and is suited for high-density recording.

[0188] In addition, a magnetic storage apparatus which uses such a magnetic recording medium can cope with the demands of high-density recording, and enable magnetic recording and reproduction of information with a high sensitivity.

[0189] Next, a description will be given of a seventh embodiment of the magnetic recording medium according to the present invention. In this seventh embodiment, at least one of the ferromagnetic layer and the magnetic layer of the first or second embodiment described above has a granular layer structure. The granular layer structure employed in this seventh embodiment has ferromagnetic crystal grains uniformly distributed within a non-magnetic base material, so as to further isolate the magnetic grains.

[0190] In a case where both the ferromagnetic layer and the magnetic layer have the granular layer structure, the magnetization directions of the granular layers can be made mutually parallel or mutually antiparallel, similarly to the first and second embodiments described above, by making the non-magnetic coupling layer which is made of Ru or the like and disposed between the granular layers to have a predetermined thickness. As a result, it is possible to increase the effective volume, thereby improving the thermal stability of written bits and reducing the medium noise.

[0191] It is not essential for both the ferromagnetic layer and the magnetic layer to have the granular layer structure, and the granular layer structure may be employed for only one of the ferromagnetic layer and the magnetic layer. When using only one granular layer, it is desirable to make the magnetic layer, which forms the recording layer, to have the granular layer structure.

[0192] In this embodiment, the granular layer is magnetically exchange coupled in an opposite magnetization direction (antiparallel) to that of the other granular layer or the CoCr-based magnetic layer, so as to improve the thermal stability of the written bits. In other words, this embodiment is provided with a pinning structure for improving the thermal stability performance of the magnetic recording medium, and is also provided with the granular layer structure for further reducing the medium noise.

[0193] The granular layer structure refers to a layer structure in which ferromagnetic crystal grains are uniformly distributed within a non-magnetic base material, as taught in a Japanese Laid-Open Patent Application No.10-92637. A granular medium is obtained by applying this granular layer structure to the recording medium of the magnetic storage apparatus. In the conventional recording medium which uses a CoCr-based magnetic material for the magnetic recording layer, the Co and Cr segragations are used to promote isolation of the magnetic grains and to reduce the noise. But in the conventional recording medium, it was difficult to obtain a desired isolation state of the magnetic grains.

[0194] On the other hand, in the granular medium according to the present invention, the ferromagnetic crystal grains are positively isolated by uniformly distributing the ferromagnetic crystal grains (metal) within the base material such as SiO_2 (ceramic material), and thus, it is possible to realize a medium with extremely low noise.

[0195] FIG. 33 is a cross sectional view showing an important part of the seventh embodiment of the magnetic recording medium according to the present invention.

[0196] The magnetic recording medium includes a non-magnetic substrate 401, a first seed layer 402, a NiP layer 403, a second seed layer 404, an underlayer 405, a non-magnetic intermediate layer 406, a ferromagnetic layer 407, a non-magnetic coupling layer 408, a magnetic layer 409, a protection layer 410, and a lubricant layer 411 which are stacked in this order as shown in FIG. 33.

[0197] For example, the non-magnetic substrate 401 is made of Al, Al alloy or glass. The non-magnetic substrate 401 may or may not be mechanically textured.

[0198] The first seed layer 402 is made of NiP, for example, especially in the case where the non-magnetic substrate 401 is made of glass. The NiP layer 403 may or may not be oxidized and may or may not be mechanically textured. The second seed layer 404 is provided to promote a (001) or a (112) texture of the underlayer 405 when the

underlayer 405 is made of an alloy having the B2 structure, such as NiAl and FeAl. The second seed layer 404 is made of a material similar to that of the first seed layer 402.

[0199] In a case where the magnetic recording medium is a magnetic disk, the mechanical texturing provided on the non-magnetic substrate 401 or the NiP layer 403 is made in a circumferential direction of the disk, that is, in a direction in which tracks of the disk extend.

[0200] The non-magnetic intermediate layer 406 is provided to further promote epitaxy, narrow the grain distribution width of the magnetic layer 409, and orient the anisotropy axes of the magnetic layer 409 along a plane parallel to the recording surface of the magnetic recording medium. However, it is not essential to provide this non-magnetic intermediate layer 406. This non-magnetic intermediate layer 406 is made of a hcp structure alloy such as CoCr-M, where M = B, Mo, Nb, Ta, W, Cu or alloys thereof, and has a thickness in a range of 1 to 5 nm.

[0201] The ferromagnetic layer 407 may be made of a granular layer which is formed by uniformly distributing ferromagnetic crystal grains into a non-magnetic base material. In this case, the ferromagnetic crystal grains may be made of Co, Ni, Fe, Ni-based alloys, Fe-based alloys, or Co-based alloys such as CoCrTa, CoCrPt and CoCrPt-M, where M = B, Mo, Nb, Ta, W, Cu or alloys thereof. It is preferable that the grain diameter of the ferromagnetic crystal grain is in a range of approximately 2 to 30 nm. Further, the non-magnetic base material may be made of a ceramic material such as SiO_2, Al_2O_3 and MgO or an oxide material such as NiO. On the other hand, the ferromagnetic layer 407 may be made of a CoCr-based magnetic material if not employing the granular layer structure.

[0202] The granular layer structure changes form depending on fundamental physical constants or properties, such as cohesive energy, surface energy and elastic strain energy of the ferromagnetic crystal grains and the non-magnetic base material. Accordingly, an extremely large number of combinations of the magnetic material used for the ferromagnetic crystal grains and the ceramic or oxide material used for the non-magnetic base material exist, and the combination may be appropriately adjusted to suit the needs.

[0203] It is preferable that the granular layer structure is used with priority for the magnetic layer 409, in which case the ferromagnetic layer 407 may be made of a CoCr-based magnetic material as described above. The reason for the preferable use of the granular layer structure for the magnetic layer 409 is because, due to the exchange coupling caused by the provision of the non-magnetic coupling layer 408, it is the uppermost magnetic layer 409 which contributes most to the noise reduction.

[0204] Of course, the ferromagnetic layer 407 and the magnetic layer 409 are not limited to a single-layer structure, and a multi-layer structure may be used for each of the ferromagnetic layer 407 and the magnetic layer 409.

[0205] The non-magnetic coupling layer 408 is made of Ru, Rh, Ir, Ru-based alloys, Rh-based alloys, Ir-based alloys, or the like. For example, the non-magnetic coupling layer 408 may be added with a ceramic material such as SiO_2 and Al_2O_3 or an oxide material such as NiO which are used for the granular layer proposed in the Japanese Laid-Open Patent Application No.10-149526. The addition of the ceramic or oxide material to the non-magnetic coupling layer 408 promotes the epitaxial growth of the non-magnetic coupling layer 408 and the magnetic layer 409, thereby further improving the signal-to-noise (S/N) ratio of the magnetic recording medium.

[0206] The protection layer 410 and the lubricant layer 411 are similar to those of the first and second embodiments described above.

[0207] The ferromagnetic layer 407 may have a thickness in a range of approximately 2 to 10 nm, and the magnetic layer 409 may have a thickness in a range of approximately 5 to 30 nm.

[0208] In addition, the magnetization directions of the ferromagnetic layer 407 and the magnetic layer 409 may be mutually antiparallel or mutually parallel.

[0209] When making the magnetization directions of the ferromagnetic layer 407 and the magnetic layer 409 mutually antiparallel, the non-magnetic coupling layer 408 desirably is made of a material selected from a group of Ru, Rh, Ir, Ru-based alloys, Rh-based alloys and Ir-based alloys, and has a thickness in a range of approximately 0.4 to 1.0 nm.

[0210] When making the magnetization directions of the ferromagnetic layer 407 and the magnetic layer 409 mutually parallel, the non-magnetic coupling layer 408 desirably is made of a material selected from a group of Ru, Rh, Ir, Ru-based alloys, Rh-based alloys and Ir-based alloys, and has a thickness in a range of approximately 0.2 to 0.4 nm and 1.0 to 1.7 nm. Ru is desirably used for the non-magnetic coupling layer 408.

[0211] The number of exchange layer structures having the granular layer structure described above is of course not limited to one, and first and second exchange layer structures of the second embodiment described above may be provided with the granular layer structure. In this case, it is preferable that the magnetic anisotropy of the granular layer in the second exchange layer structure is set smaller than that of the granular layer in the first exchange layer structure which is disposed under the second exchange layer structure. Furthermore, it is preferable that the remanence magnetization and thickness product of the granular layer in the second exchange layer structure is set smaller than that of the granular layer in the first exchange layer structure which is disposed under the second exchange layer structure.

[0212] Further, the present invention is not limited to these embodiments, but various variations and modifications may be made without departing from the scope of the present invention.

Claims

1. A magnetic recording medium characterized by:

   at least one exchange layer structure; and
   a magnetic layer formed on said exchange layer structure,
   said exchange layer structure comprising:

      a ferromagnetic layer; and
      a non-magnetic coupling layer provided on said ferromagnetic layer and under said magnetic layer.

2. The magnetic recording medium as claimed in claim 1, characterized in that said ferromagnetic layer and said magnetic layer have antiparallel magnetizations.

3. The magnetic recording medium as claimed in claim 1 or 2, characterized in that said ferromagnetic layer is made of a material selected from a group consisting of Co, Ni, Fe, Ni-based alloys, Fe-based alloys, and Co-based alloys including CoCrTa, CoCrPt and CoCrPt-M, where M = B, Mo, Nb, Ta, W, Cu or alloys thereof.

4. The magnetic recording medium as claimed in any of claims 1 to 3, characterized in that said non-magnetic coupling layer is made of a material selected from a group of Ru, Rh, Ir, Ru-based alloys, Rh-based alloys, and Ir-based alloys.

5. The magnetic recording medium as claimed in any of claims 1 to 4, characterized in that said non-magnetic coupling layer has a thickness in a range of 0.4 to 1.0 nm.

6. The magnetic recording medium as claimed in any of claims 1 to 5, characterized in that said magnetic layer is made of a material selected from a group of Co, and Co-based alloys including CoCrTa, CoCrPt and CoCrPt-M, where M = B, Mo, Nb, Ta, W, Cu or alloys thereof.

7. The magnetic recording medium as claimed in any of claims 1 to 6, further characterized by:

   a substrate; and
   an underlayer provided above said substrate,
   said exchange layer structure being provided above said underlayer.

8. The magnetic recording medium as claimed in claim 7, further characterized by:

   a non-magnetic intermediate layer interposed between said underlayer and said exchange layer structure,
   said non-magnetic intermediate layer having a hcp structure alloy selected from a group of CoCr-M, where M = B, Mo, Nb, Ta, W or alloys thereof, and having a thickness in a range of 1 to 5 nm.

9. The magnetic recording medium as claimed in any of claims 1 to 8, characterized by at least a first exchange layer structure and a second exchange layer structure interposed between said first exchange layer structure and said magnetic layer, wherein a ferromagnetic layer of said second exchange layer structure has a magnetic anisotropy lower than that of a ferromagnetic layer of said first exchange layer structure, and magnetizations of the ferromagnetic layers of said first and second exchange layer structures are antiparallel.

10. The magnetic recording medium as claimed in any of claims 1 to 8, characterized by at least a first exchange layer structure and a second exchange layer structure interposed between said first exchange layer structure and said magnetic layer, wherein a remanent magnetization and thickness product of a ferromagnetic layer of said second exchange layer structure is smaller than that of a ferromagnetic layer of said first exchange layer structure, and magnetizations of the ferromagnetic layers of said first and second exchange layer structures are antiparallel.

11. A magnetic recording medium comprising a magnetic layer, characterized by:

    a first exchange layer structure; and
    a second exchange layer structure provided between said first exchange layer structure and said magnetic layer,

wherein a ferromagnetic layer of said second exchange layer structure has a magnetic anisotropy lower than that of a ferromagnetic layer of said first exchange layer structure, and magnetizations of the ferromagnetic layers of said first and second exchange layer structures are antiparallel.

12. A magnetic recording medium comprising a substrate, and an underlayer disposed above said substrate, characterized by:

a magnetic layer structure including at least a bottom ferromagnetic layer provided on the underlayer and having a remanent magnetization and thickness product $Mr_i\delta_i$, and a top ferromagnetic layer disposed above the bottom ferromagnetic layer and having a remanent magnetization and thickness product $Mr_j\delta_j$, wherein a relationship $Mr\delta \fallingdotseq \Sigma(Mr_i\delta_i - Mr_j\delta_j)$ is satisfied, where $Mr\delta$ denotes a total remanent magnetization and thickness product of the magnetic layer structure, so that magnetization directions of adjacent ferromagnetic layers in the magnetic layer structure are closely antiparallel.

13. The magnetic recording medium as claimed in claim 12, further characterized by:

a non-magnetic coupling layer interposed between adjacent ferromagnetic layers of the magnetic layer structure, so that antiparallel magnetic interaction is induced thereby.

14. The magnetic recording medium as claimed in claim 13, characterized in that said non-magnetic coupling layer is made essentially of Ru with a thickness of approximately 0.4 to 1.0 nm.

15. The magnetic recording medium as claimed in claim 13, characterized in that said non-magnetic coupling layer is made of a material selected from a group of Ru, Rh, Ir, Cu, Cr and alloys thereof.

16. The magnetic recording medium as claimed in any of claims 12 to 15, characterized in that each of the ferromagnetic layers of the magnetic layer structure is made of a material selected from a group of Co, Fe, Ni, CoCrTa, CoCrPt and CoCrPt-M, where M=B, Cu, Mo, Nb, Ta, W and alloys thereof.

17. The magnetic recording medium as claimed in any of claims 12 to 16, characterized in that at least one of the ferromagnetic layers of the magnetic layer structure is made up of a plurality of ferromagnetic layers which are in contact with each other and ferromagnetically coupled.

18. The magnetic recording medium as claimed in any of claims 12 to 17, characterized in that the $Mr_j\delta_j$ of the top ferromagnetic layer is largest among remanent magnetization and thickness products of other ferromagnetic layers of the magnetic layer structure.

19. A method of magnetically recording information on a magnetic recording medium, characterized by:

a step of switching magnetization direction of at least one of ferromagnetic layers which form a magnetic layer structure of the magnetic recording medium and have antiparallel magnetization directions.

20. A method of producing a magnetic recording medium having a substrate, an underlayer and a magnetic layer structure, characterized by the steps of:

(a) forming the magnetic layer structure to include at least a bottom ferromagnetic layer provided on the underlayer and having a remanent magnetization and thickness product $Mr_i\delta_i$, and a top ferromagnetic layer disposed above the bottom ferromagnetic layer and having a remanent magnetization and thickness product $Mr_j\delta_j$, wherein a relationship $Mr\delta \fallingdotseq \Sigma(Mr_i\delta_i - Mr_j\delta_j)$ is satisfied, where $Mr\delta$ denotes a total remanent magnetization and thickness product of the magnetic layer structure, so that magnetization directions of adjacent ferromagnetic layers in the magnetic layer structure are closely antiparallel; and
(b) forming the underlayer and the magnetic structure by sequential sputtering.

21. A magnetic recording medium characterized by:

at least one exchange layer structure and a magnetic layer provided on the exchange layer structure, said exchange layer structure including a ferromagnetic layer and a non-magnetic coupling layer provided on the ferromagnetic layer; and

a magnetic bonding layer provided between the ferromagnetic layer and the non-magnetic coupling layer and/or between the non-magnetic coupling layer and the magnetic layer,

said magnetic bonding layer having a magnetization direction parallel to the ferromagnetic layer and the magnetic layer.

22. The magnetic recording medium as claimed in claim 21, characterized in that said magnetic bonding layer is made of a material different from those of the ferromagnetic layer and the magnetic layer.

23. The magnetic recording medium as claimed in claim 21 or 22, characterized in that an upper magnetic bonding layer and a lower magnetic bonding layer are respectively provided above and below the non-magnetic coupling layer, and an exchange coupling between the upper magnetic bonding layer and the lower magnetic bonding layer is larger than an exchange coupling between the magnetic layer and the ferromagnetic layer.

24. The magnetic recording medium as claimed in any of claims 21 to 23, characterized in that said magnetic bonding layer is made of a material selected from a group of Co, Fe, Fe-based alloys, Ni-based alloys, and Co-based alloys including CoCrTa, CoCrPt and CoCrPt-M, where M = B, Mo, Nb, Ta, W, Cu or alloys thereof.

25. The magnetic recording medium as claimed in claim 24, characterized in that a Co or Fe concentration of the magnetic bonding layer is higher than a Co or Fe concentrations of the ferromagnetic layer and the magnetic layer.

26. A magnetic recording medium characterized by:

at least one exchange layer structure; and
a magnetic layer formed on said exchange layer structure,
said exchange layer structure comprising a ferromagnetic layer, and a non-magnetic coupling layer provided on said ferromagnetic layer and under said magnetic layer,
said ferromagnetic layer and said magnetic layer having antiparallel magnetizations,
said non-magnetic coupling layer being made of a Ru-M3 alloy, where M3 is an added element or alloy, and a lattice mismatch between said non-magnetic coupling layer and said magnetic layer and said ferromagnetic layer respectively disposed above and below said non-magnetic coupling layer is adjusted to approximately 6% or less by addition of M3.

27. A magnetic recording medium characterized by:

at least one exchange layer structure; and
a magnetic layer formed on said exchange layer structure,
said exchange layer structure comprising a ferromagnetic layer, and a non-magnetic coupling layer provided on said ferromagnetic layer and under said magnetic layer,
said ferromagnetic layer and said magnetic layer having antiparallel magnetizations,
said non-magnetic coupling layer being made of a Ru-M3 alloy, where M3 = Co, Cr, Fe, Ni, Mn or alloys thereof.

28. The magnetic recording medium as claimed in claim 26 or 27, characterized in that an amount of the element M3 added to Ru is 50 at% or less for Co, 50 at% or less for Cr, 60 at% or less for Fe, 10 at% or less for Ni, and 50 at% or less for Mn.

29. A magnetic recording medium comprising: a substrate; an underlayer disposed above the substrate; and a magnetic recording layer disposed above the underlayer, characterized in that:

said magnetic recording layer has a multi-layer structure which is separated into at least upper and lower layers by a non-magnetic separation layer,
said non-magnetic separation layer is made of a material selected from a group of Ru, Rh, Ir and alloys thereof, the upper and lower layers of the multi-layer structure separated by the non-magnetic separation layer have magnetization directions which are mutually parallel.

30. The magnetic recording medium as claimed in claim 29, characterized in that said non-magnetic separation layer has a thickness in a range of approximately 0.2 to 0.4 nm or approximately 1.0 to 1.7 nm.

31. The magnetic recording medium as claimed in claim 29 or 30, characterized in that said magnetic recording layer

is separated into an upper first magnetic recording layer and a lower second magnetic recording layer by said non-magnetic separation layer, and a thickness ratio of a thickness of the first magnetic recording layer to a thickness of the second magnetic recording layer is in a range of approximately 5:5 to 7:3 when the first and second magnetic recording layers are made of the same magnetic material.

32. A magnetic recording medium characterized by:

at least one exchange layer structure; and
a magnetic layer provided on the exchange layer structure,
said exchange layer structure including a ferromagnetic layer and a non-magnetic coupling layer provided on the ferromagnetic layer,
at least one of said ferromagnetic layer and said magnetic layer having a granular layer structure in which ferromagnetic crystal grains are uniformly distributed within a non-magnetic base material.

33. The magnetic recording medium as claimed in claim 32, characterized in that said ferromagnetic crystal grains are made of a material selected from a group of Co, Ni, Fe, Ni-based alloys, Fe-based alloys, and Co-based alloys including CoCrTa, CoCrPt and CoCrPt-M, where M = B, Mo, Nb, Ta, W, Cu and alloys thereof.

34. The magnetic recording medium as claimed in claim 32 or 33, characterized in that said non-magnetic base material is made of a material selected from a group of ceramic materials and oxide materials.

FIG.1

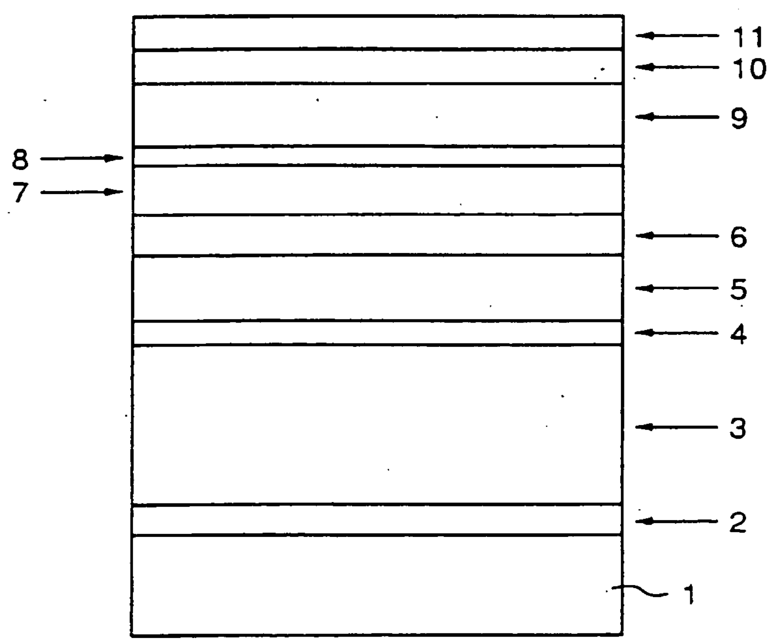


FIG. 2

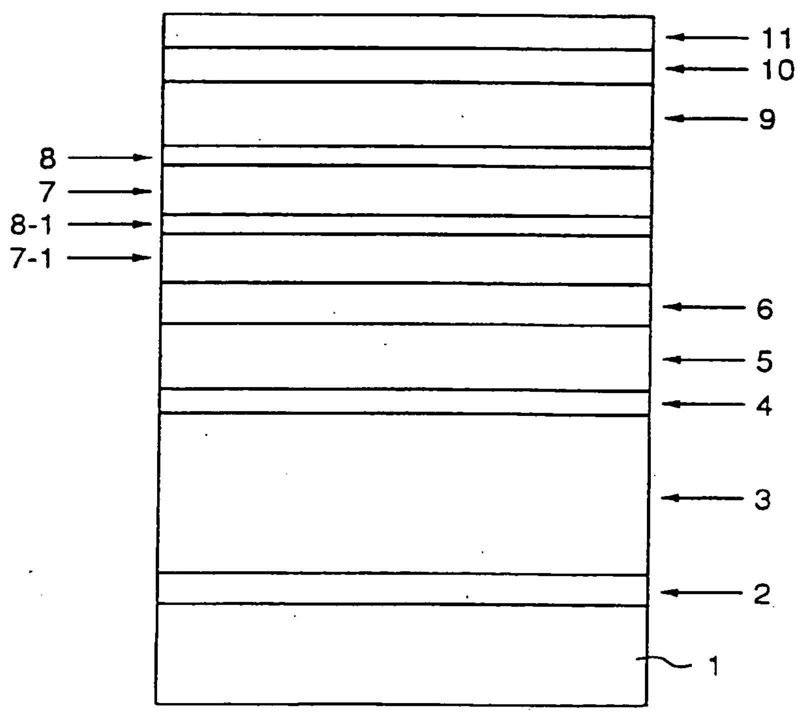


FIG.3

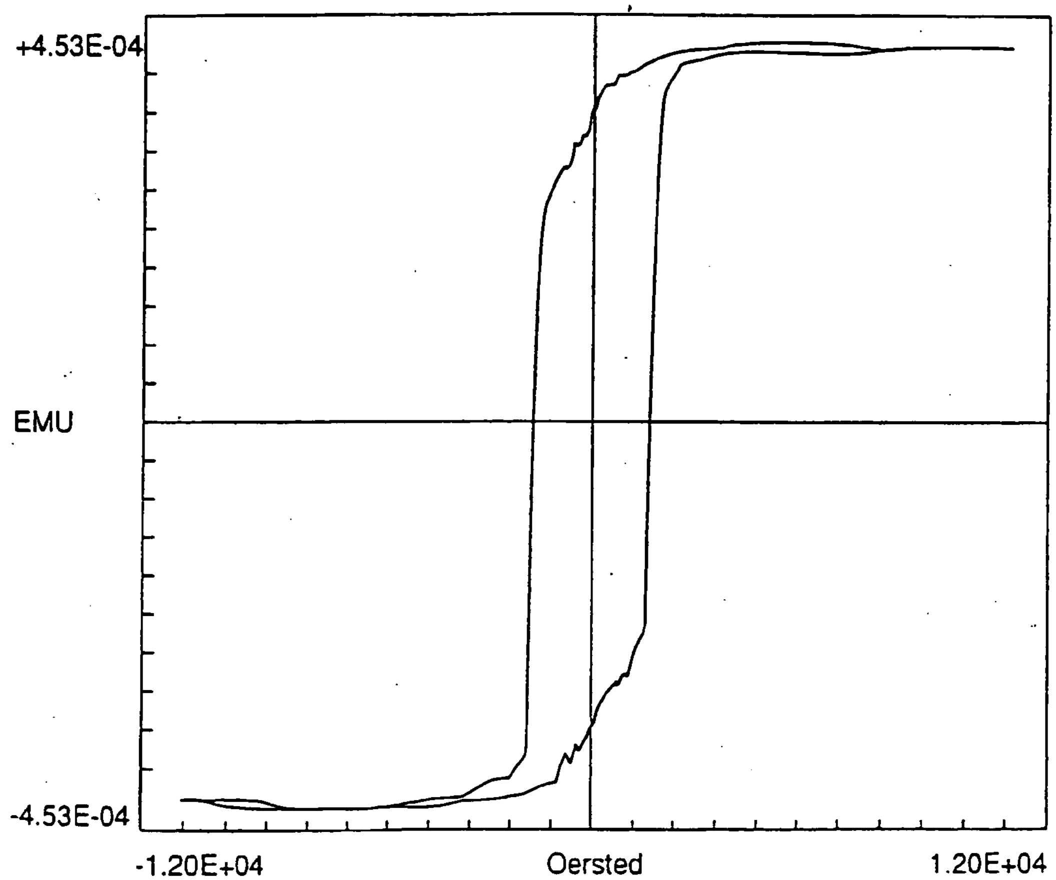


FIG.4

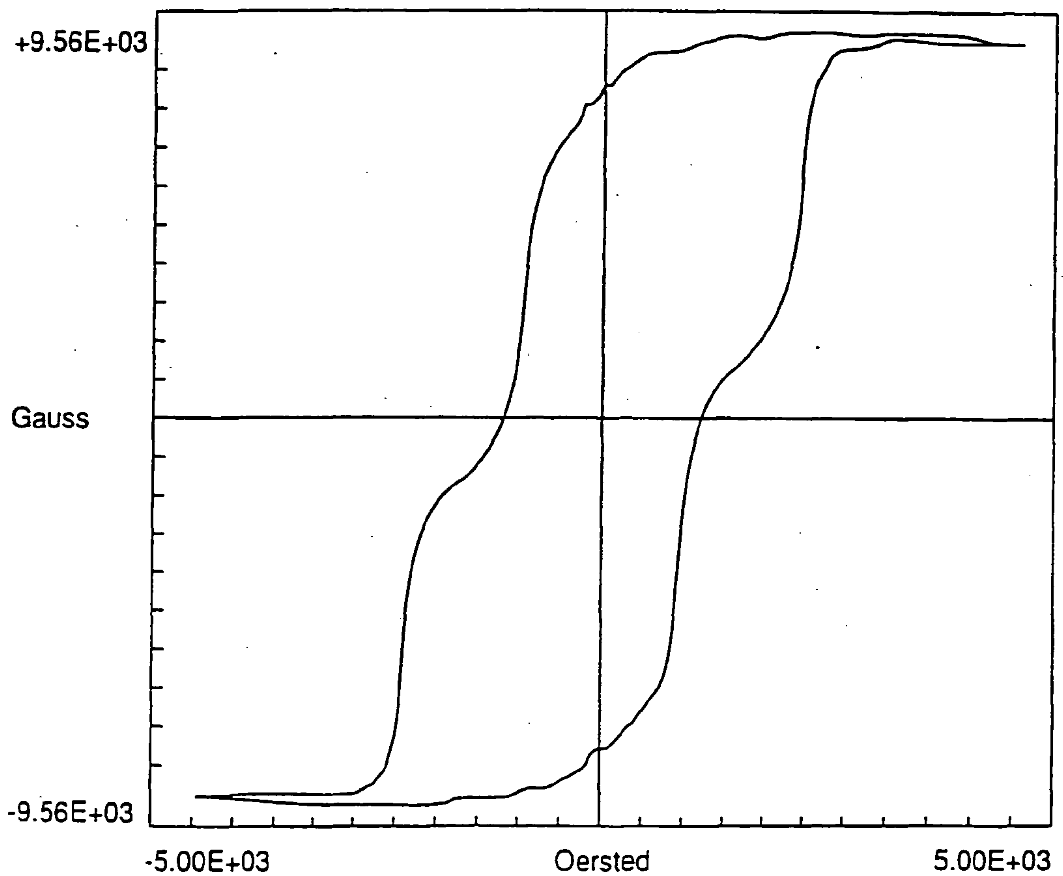


FIG.5

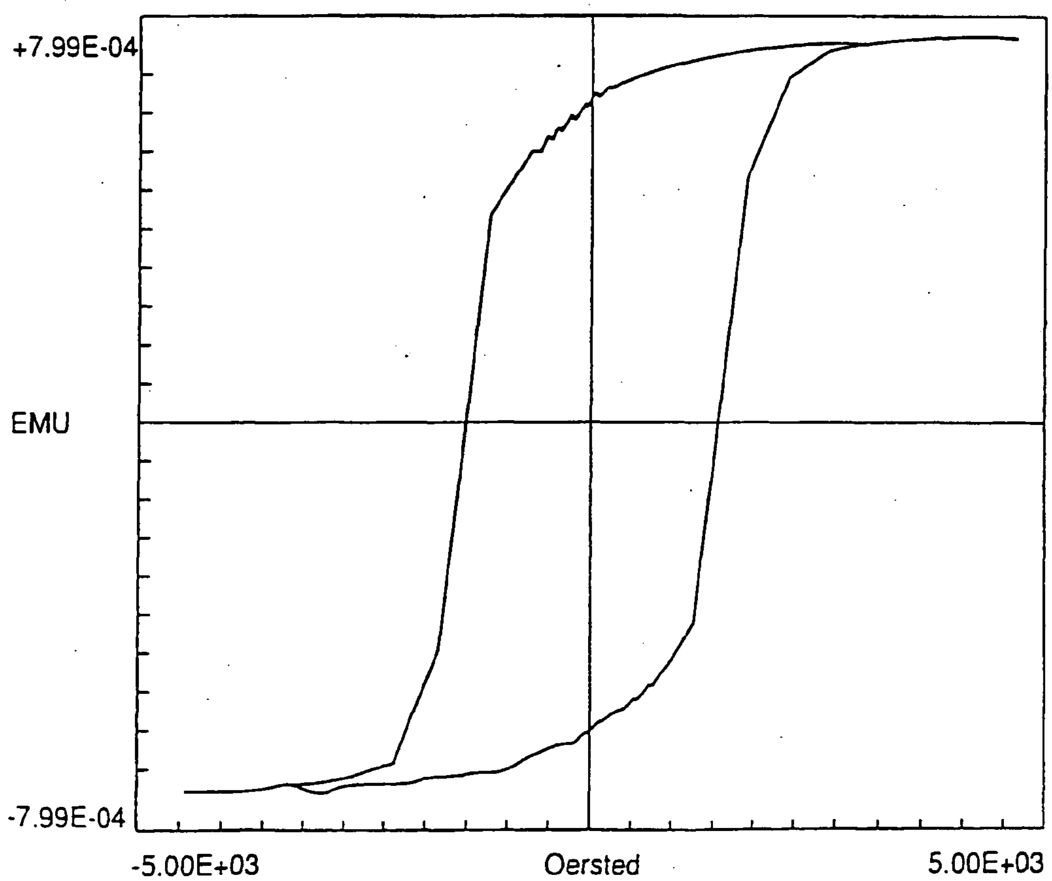


FIG.6

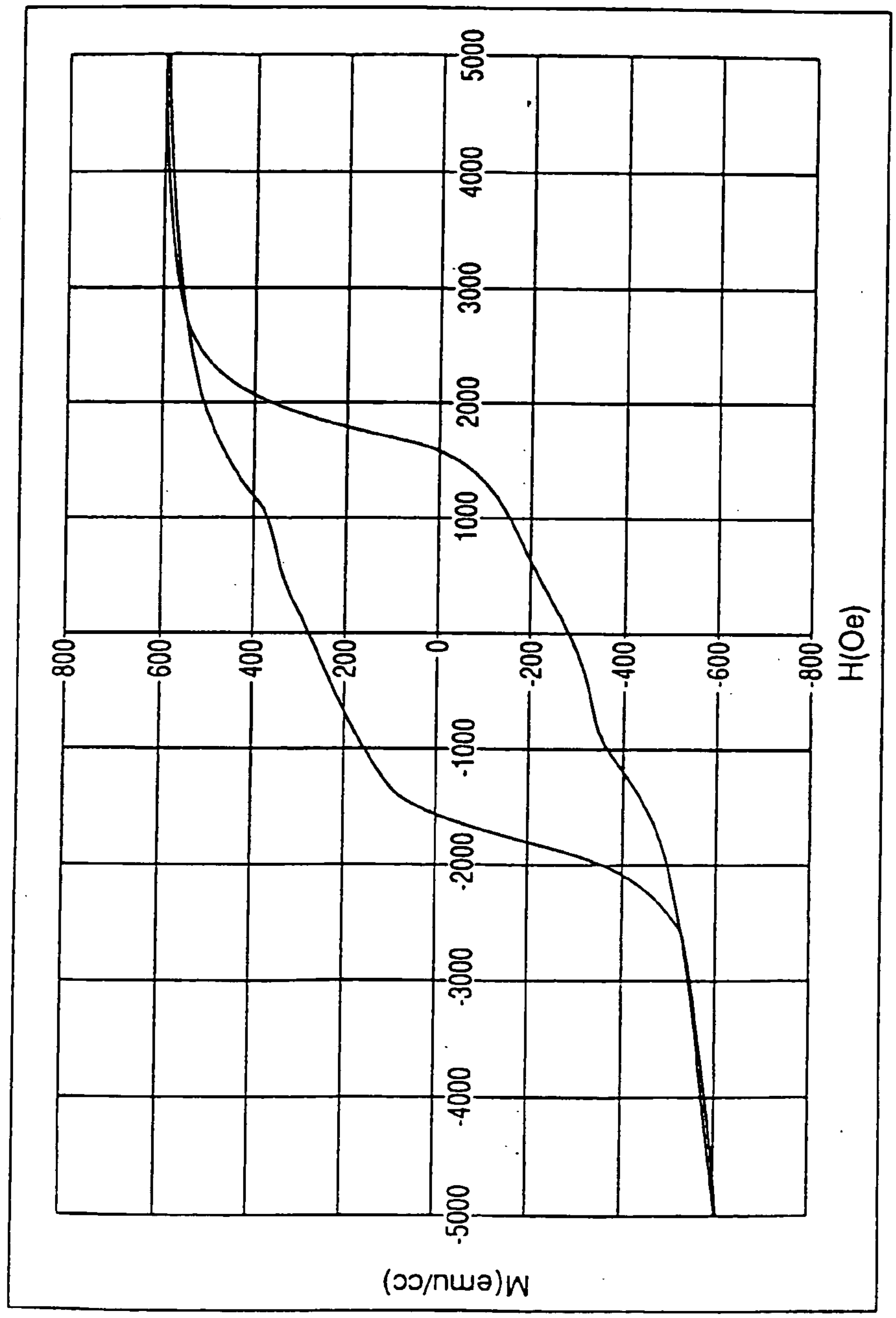

M(emu/cc)
H(Oe)
800
600
400
200
0
-200
-400
-600
-800
-5000
-4000
-3000
-2000
-1000
1000
2000
3000
4000
5000

FIG.7

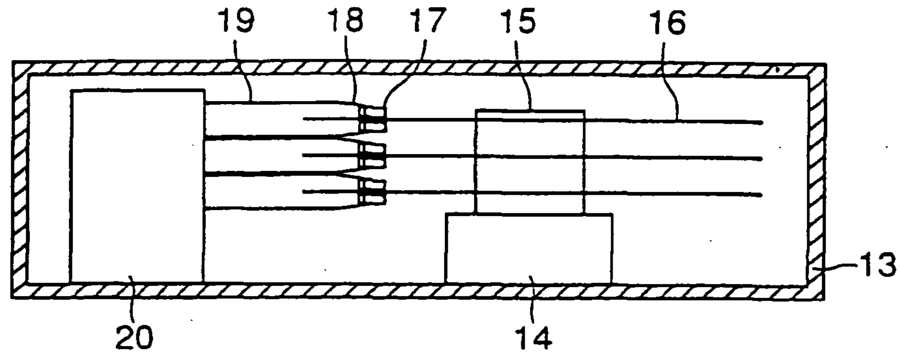


FIG.8

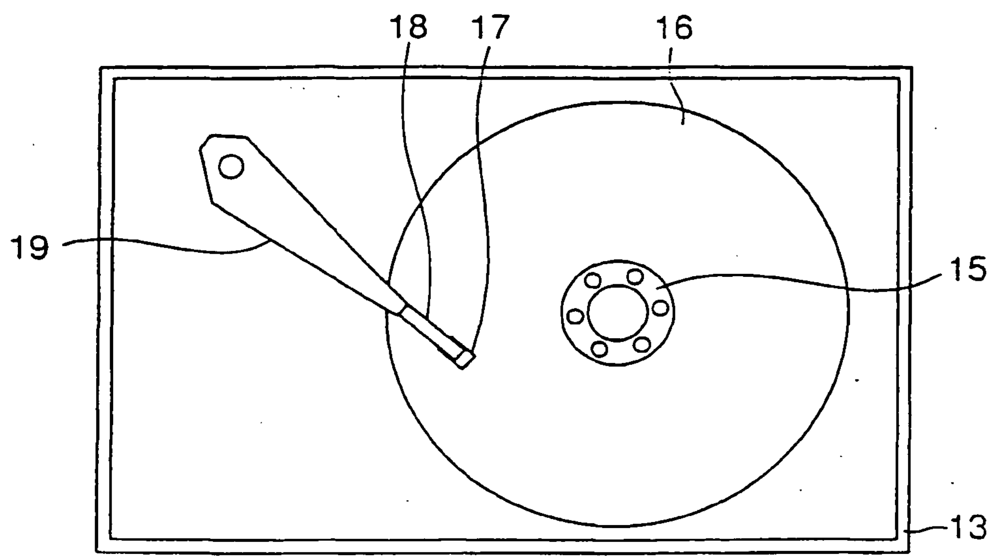
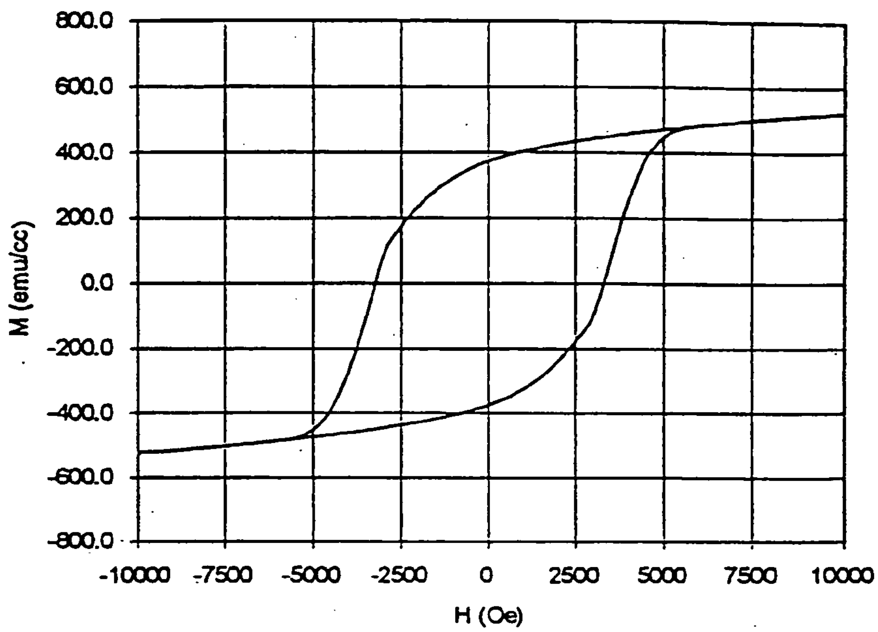


FIG.9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600.0
400.0
200.0
0.0
-200.0
-400.0
-600.0
-800.0
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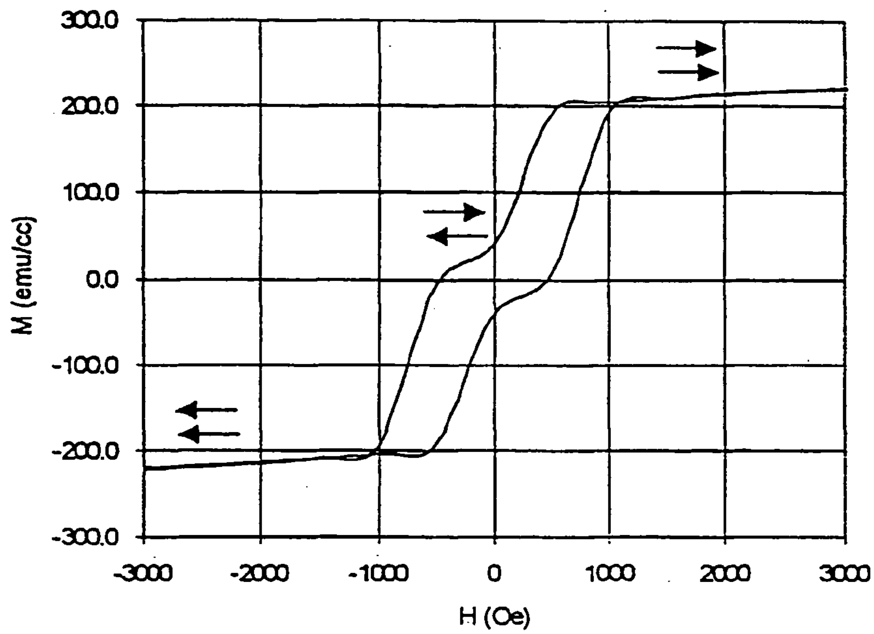
-7500
-5000
-2500
0
2500
5000
7500
10000
H (Oe)

FIG.10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200.0
100.0
0.0
-100.0
-200.0
-300.0
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-2000
-1000
0
1000
2000
3000
H (Oe)

FIG.11

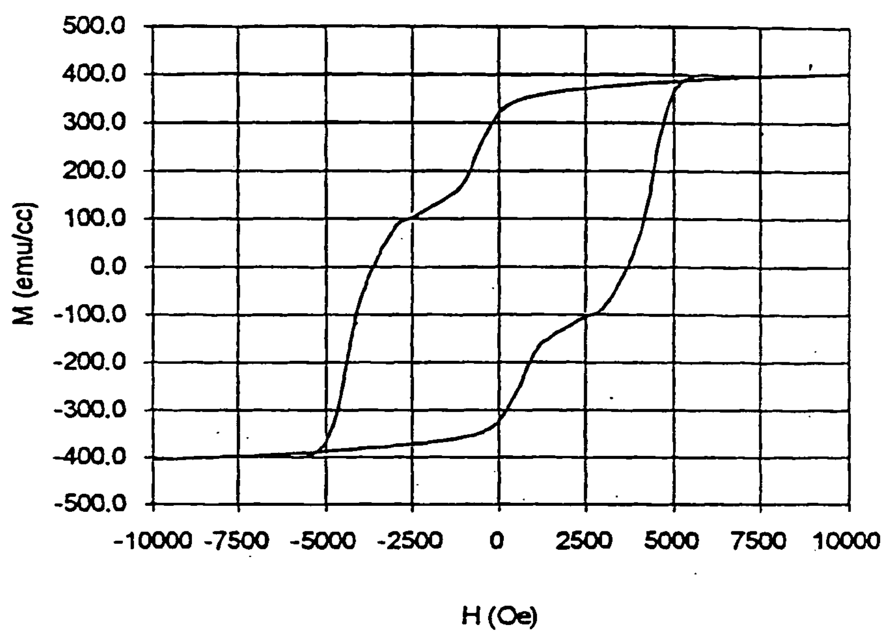
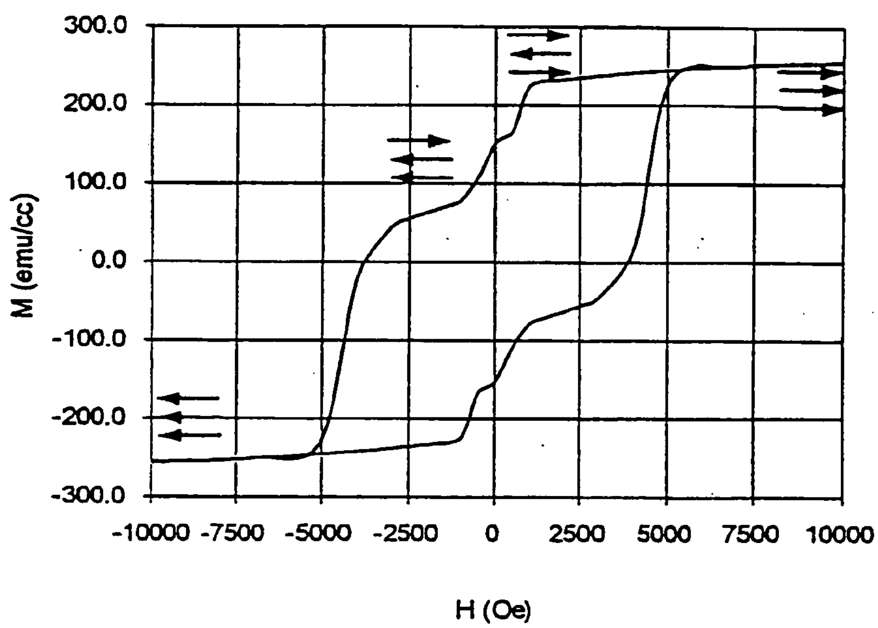

500.0
400.0
300.0
200.0
100.0
0.0
-100.0
-200.0
-300.0
-400.0
-500.0
M (emu/cc)
-10000
-7500
-5000
-2500
0
2500
5000
7500
10000
H (Oe)

FIG.12


300.0
200.0
100.0
0.0
-100.0
-200.0
-300.0
M (emu/cc)
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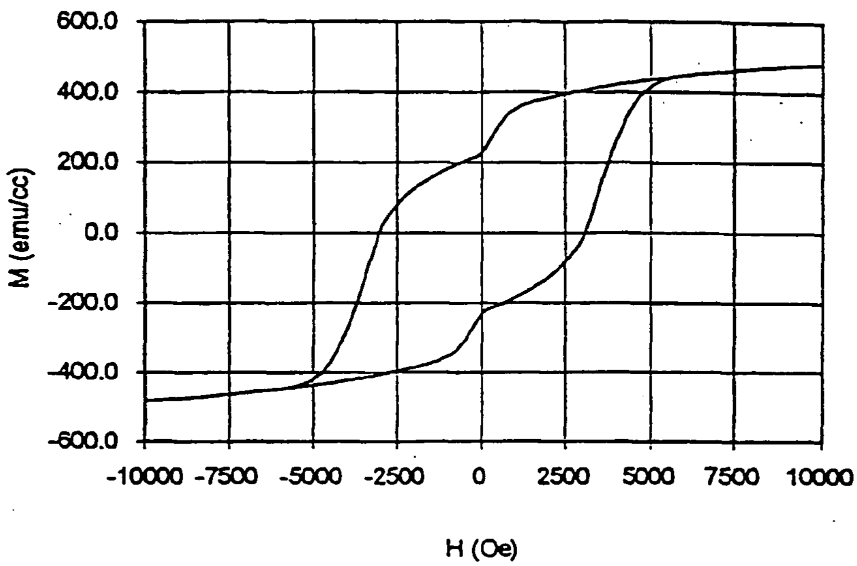
-7500
-5000
-2500
0
2500
5000
7500
10000
H (Oe)

FIG.13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400.0
200.0
0.0
-200.0
-400.0
-600.0
M (emu/cc)
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-7500
-5000
-2500
0
2500
5000
7500
10000
H (Oe)

FIG.14

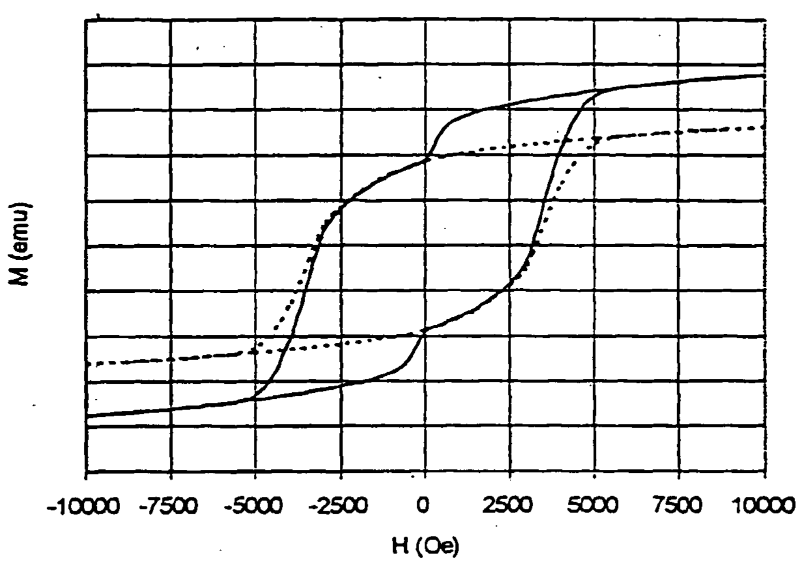
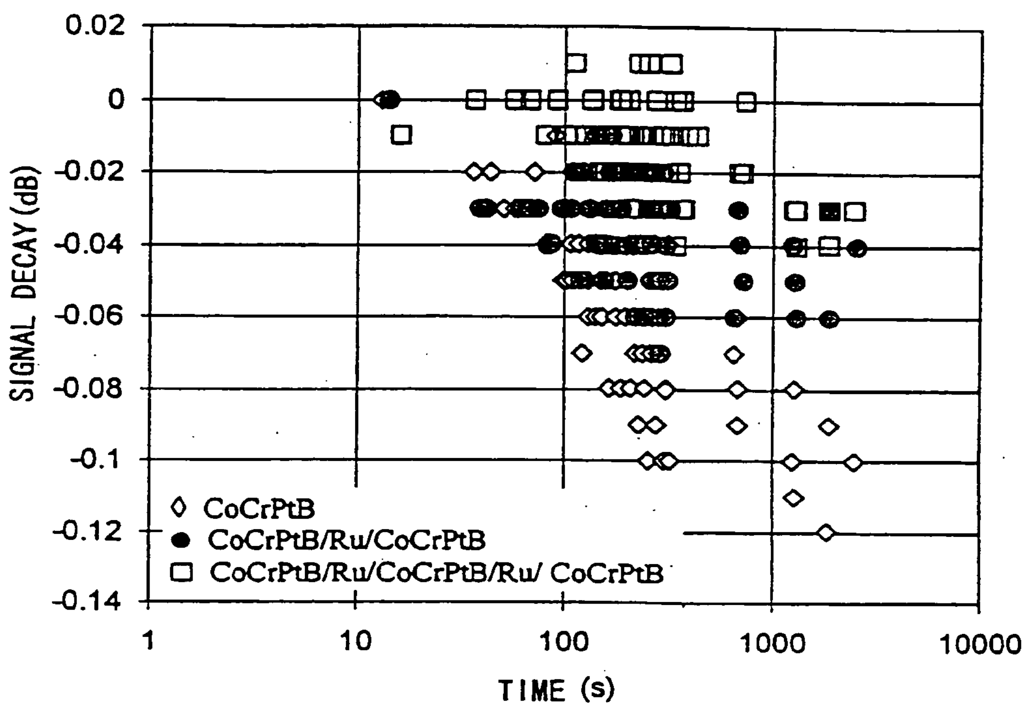


FIG.15



0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
-0.12
-0.14
SIGNAL DECAY (dB)
1
10
100
1000
10000
TIME (s)
CoCrPtB
CoCrPtB/Ru/CoCrPtB
CoCrPtB/Ru/CoCrPtB/Ru/ CoCrPtB

FIG.16

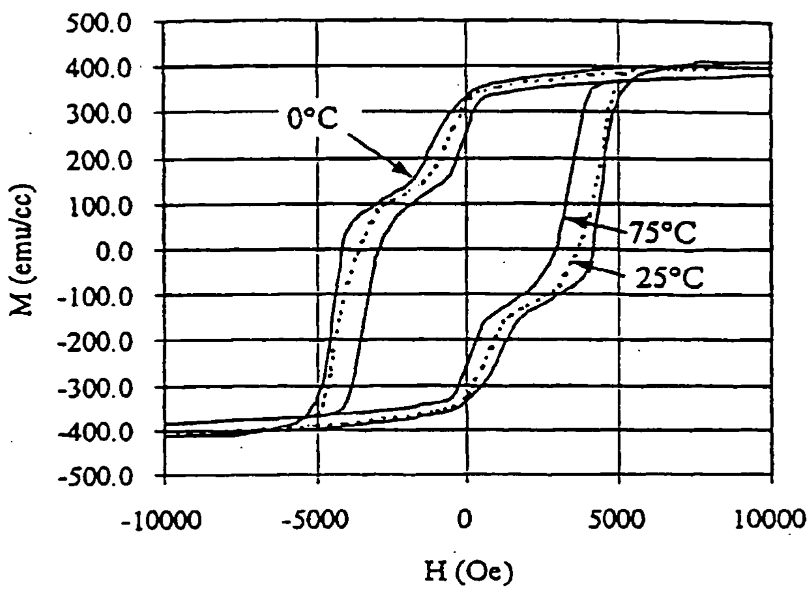

500.0
400.0
300.0
200.0
100.0
0.0
-100.0
-200.0
-300.0
-400.0
-500.0
M (emu/cc)
0°C
75°C
25°C
-10000
-5000
0
5000
10000
H (Oe)

FIG.17

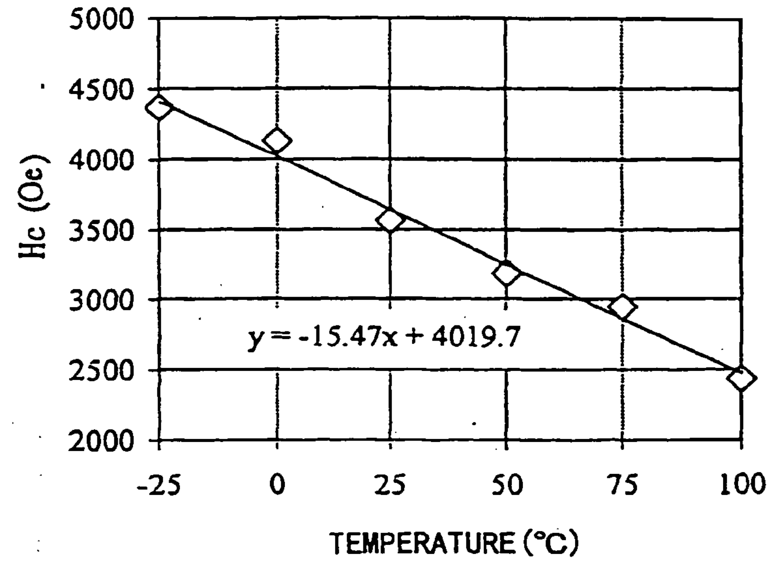

5000
4500
4000
3500
3000
2500
2000
Hc (Oe)
y = -15.47x + 4019.7
-25
0
25
50
75
100
TEMPERATURE (°C)

FIG.18

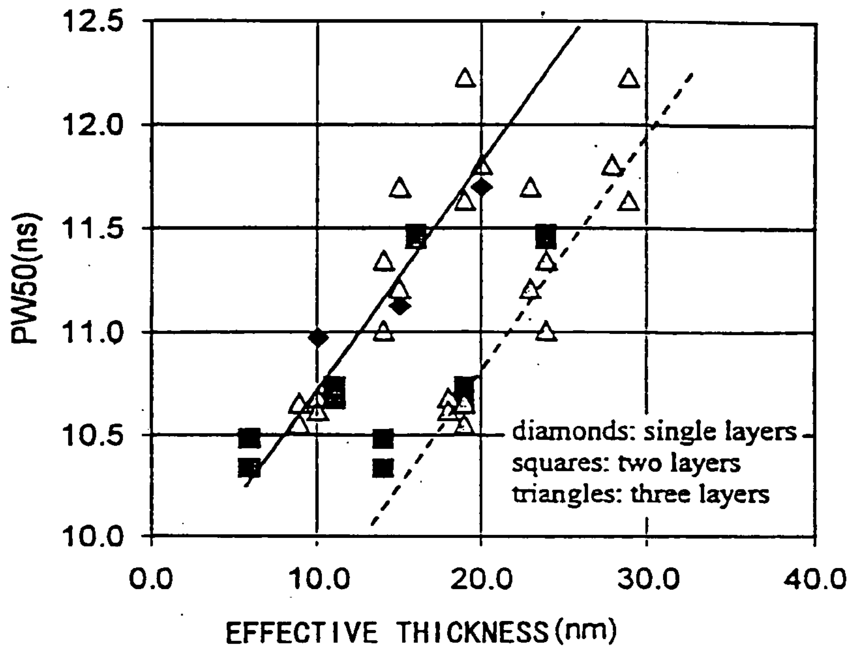

12.5
12.0
11.5
11.0
10.5
10.0
PW50(ns)
0.0
10.0
20.0
30.0
40.0
EFFECTIVE THICKNESS(nm)
diamonds: single layers
squares: two layers
triangles: three layers

FIG.19

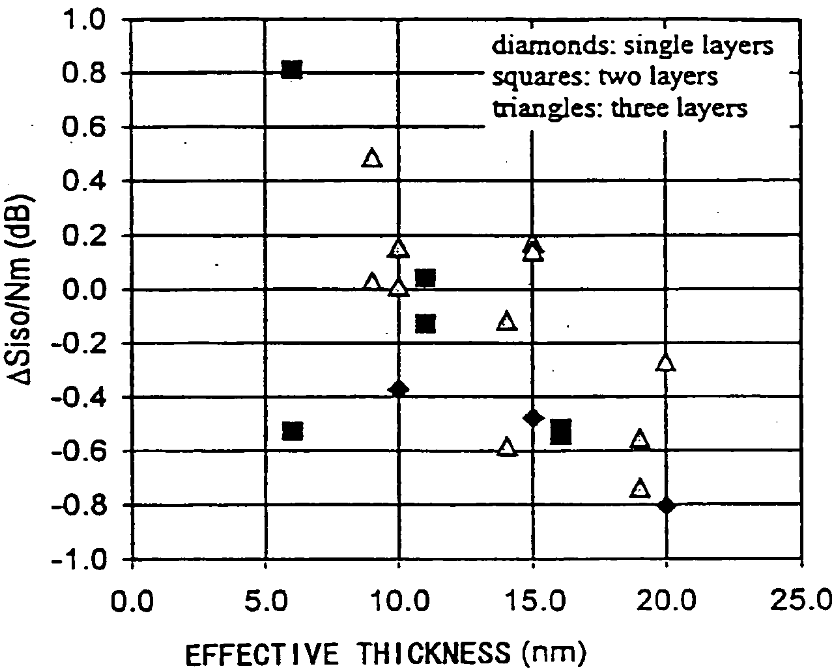

diamonds: single layers
squares: two layers
triangles: three layers
ΔSiso/Nm (dB)
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
0.0
5.0
10.0
15.0
20.0
25.0
EFFECTIVE THICKNESS (nm)

FIG.20

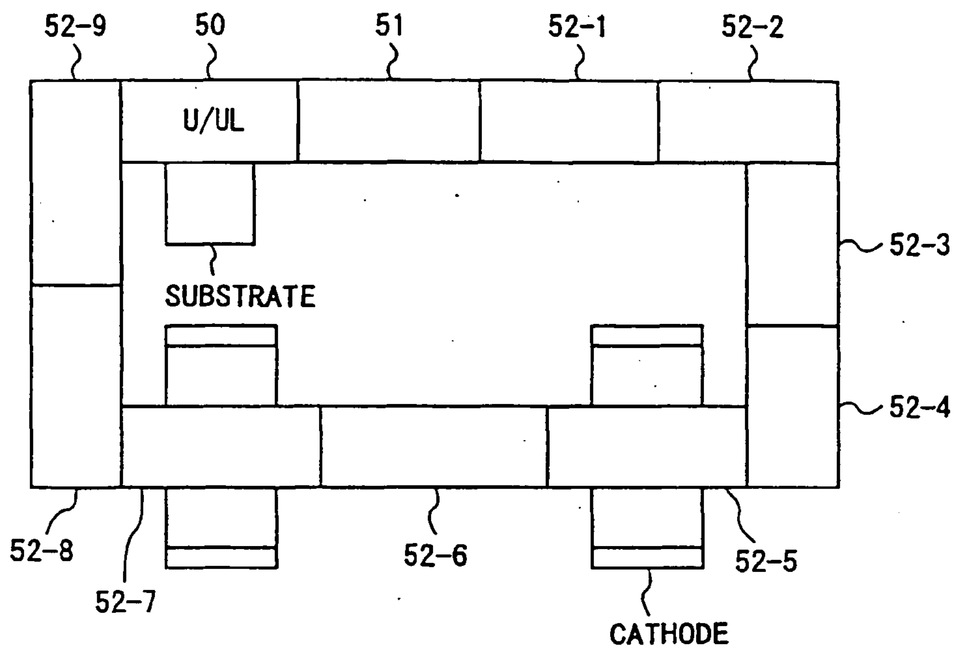
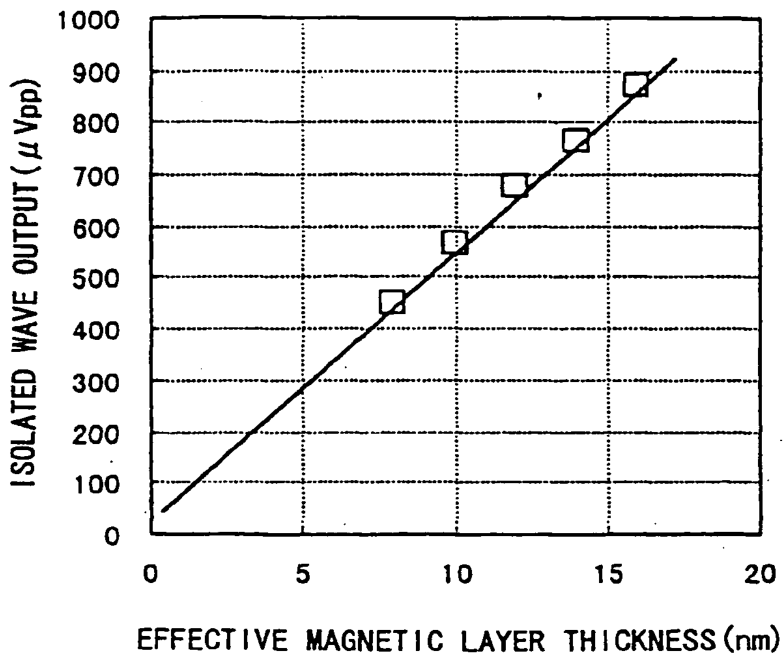

52-9
50
51
52-1
52-2
U/UL
52-3
SUBSTRATE
52-4
52-8
52-7
52-6
52-5
CATHODE

FIG.21



ISOLATED WAVE OUTPUT (μVpp)
1000
900
800
700
600
500
400
300
200
100
0
0
5
10
15
20
EFFECTIVE MAGNETIC LAYER THICKNESS (nm)

FIG.22

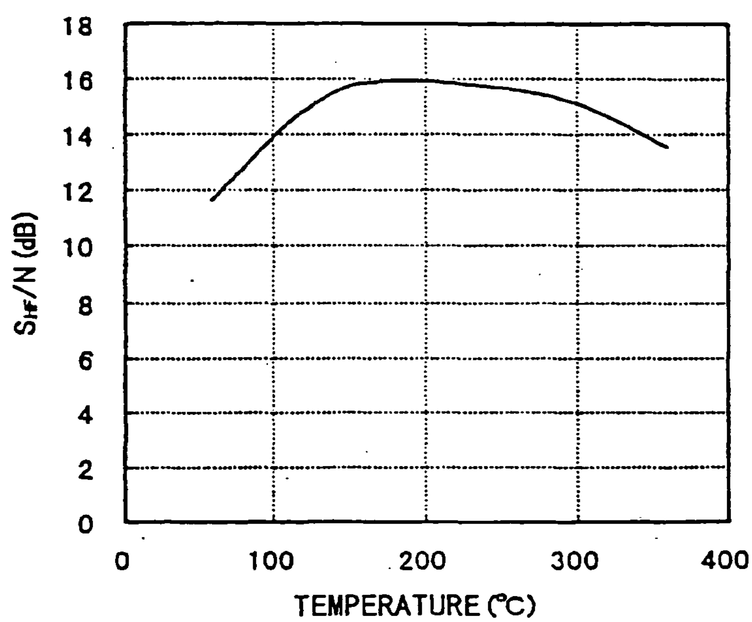


FIG.23

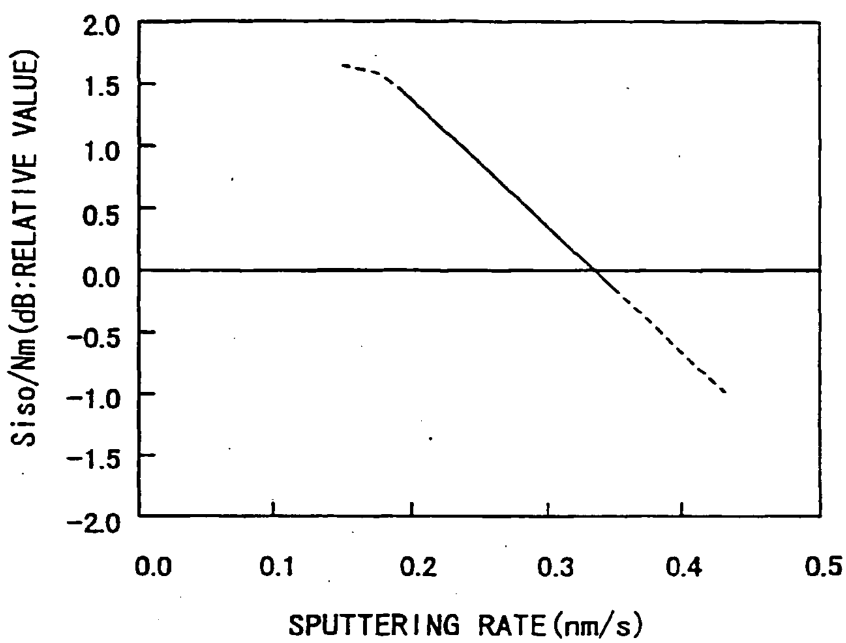

2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
Siso/Nm(dB;RELATIVE VALUE)
0.0
0.1
0.2
0.3
0.4
0.5
SPUTTERING RATE(nm/s)

FIG. 24

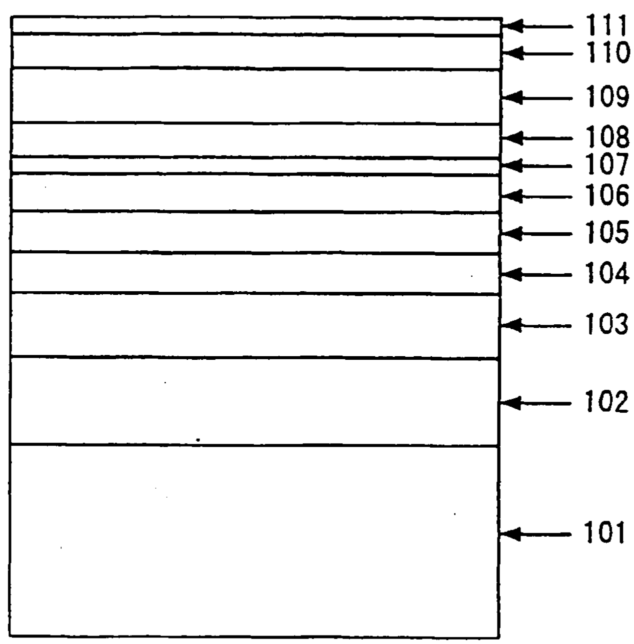


FIG. 25

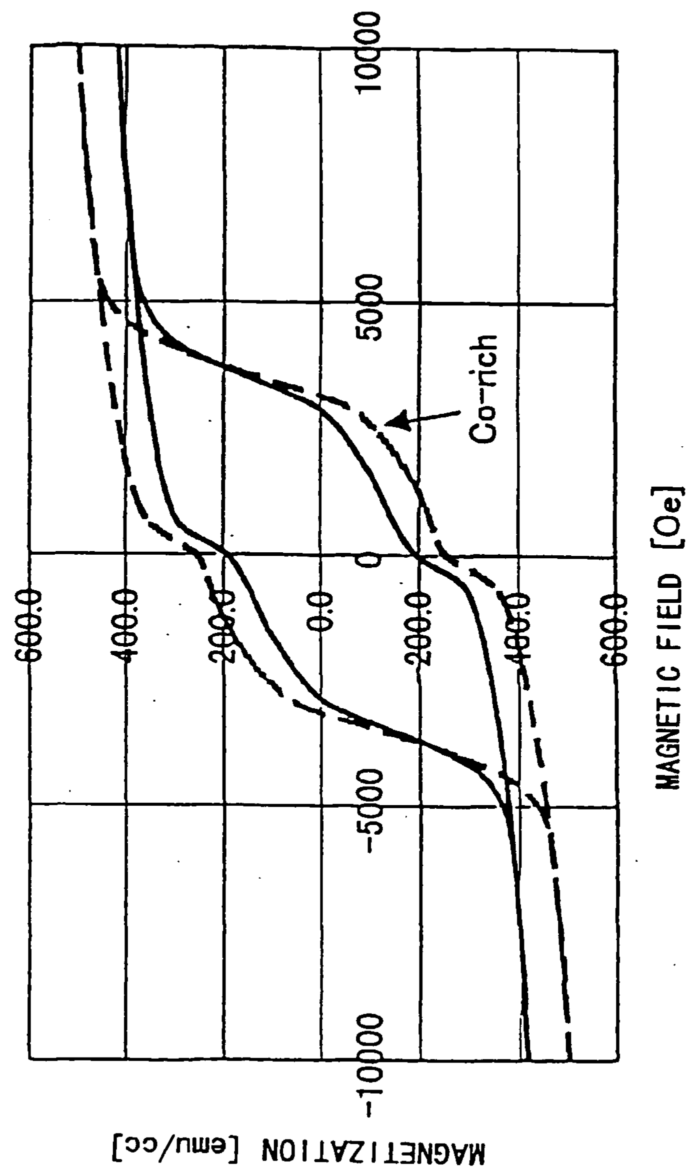

10000
5000
0
-5000
-10000
600.0
400.0
200.0
0.0
200.0
400.0
600.0
Co-rich
MAGNETIC FIELD [Oe]
MAGNETIZATION [emu/cc]

FIG. 26

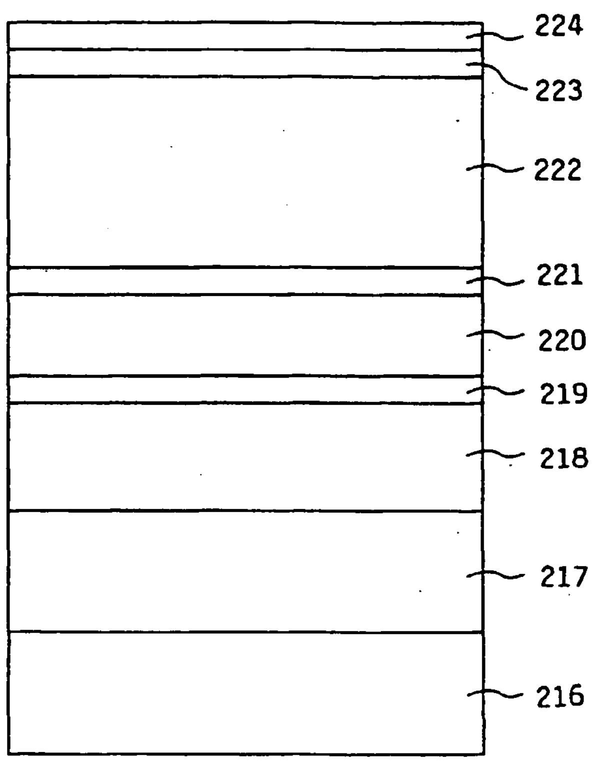


FIG. 27

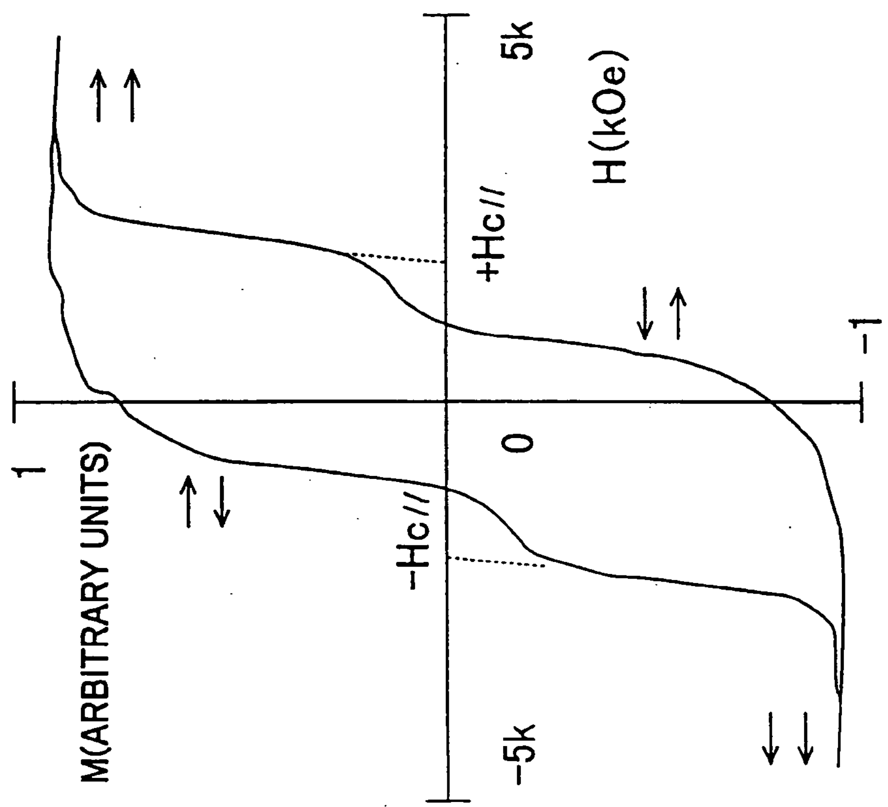


FIG. 28

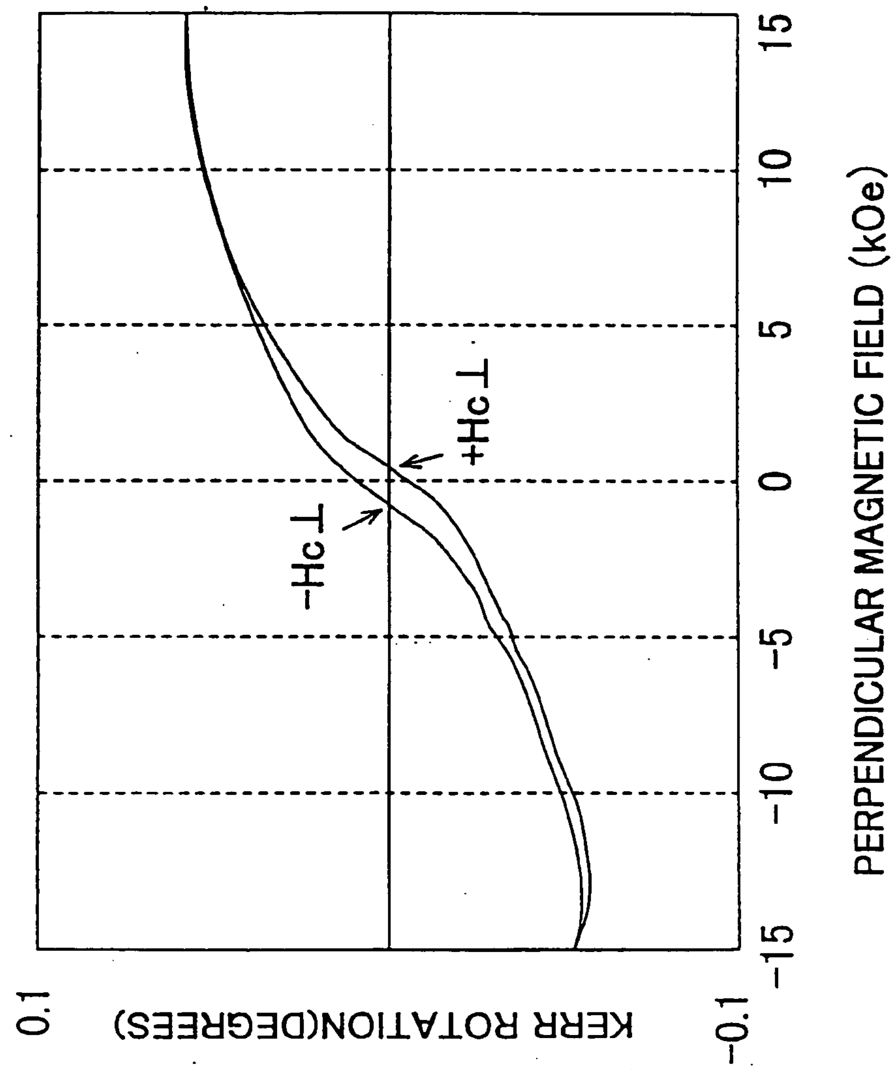

KERR ROTATION(DEGREES)
0.1
-0.1
PERPENDICULAR MAGNETIC FIELD (kOe)
-15
-10
-5
0
5
10
15
-Hc⊥
+Hc⊥

FIG. 29

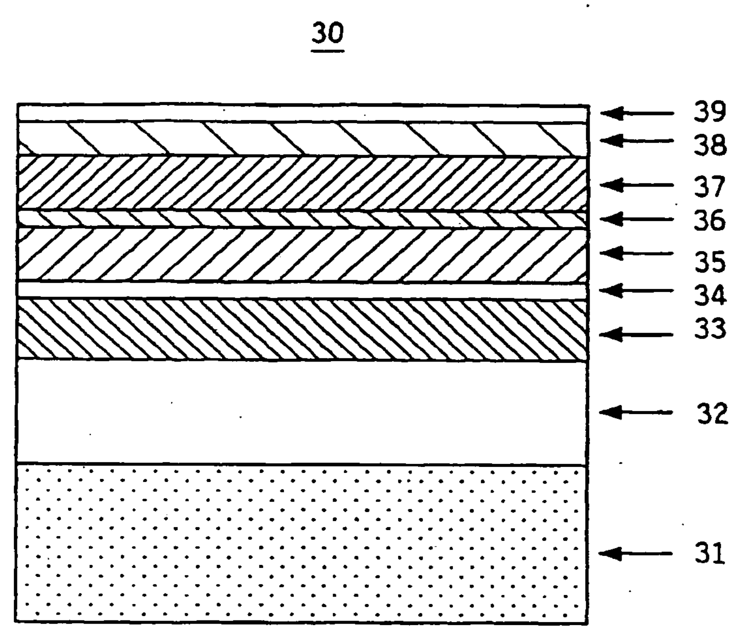


FIG. 30

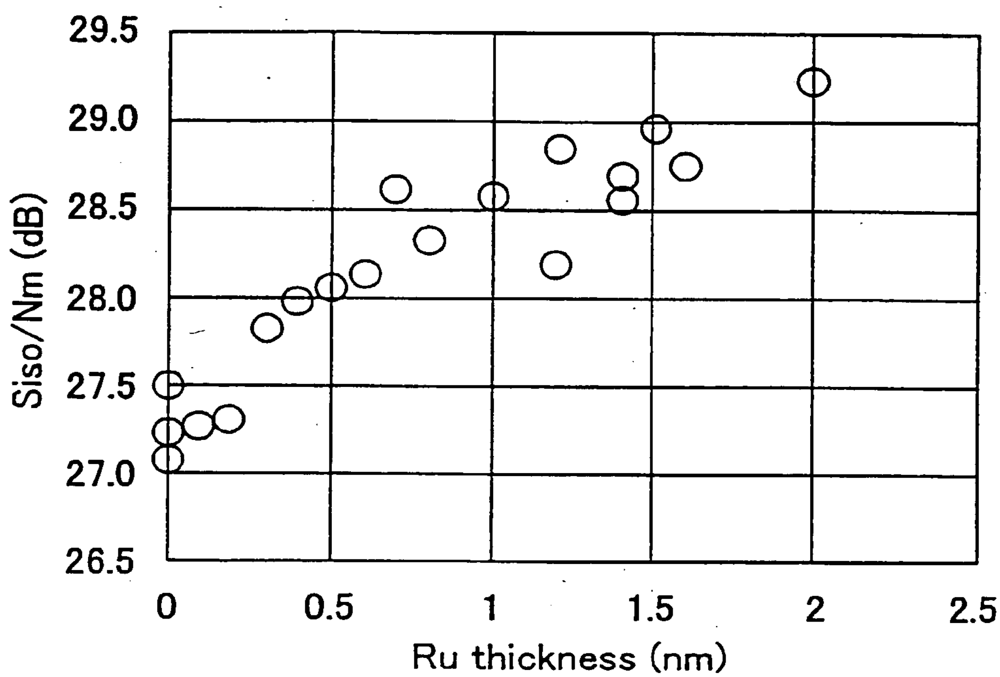

29.5
29.0
28.5
28.0
27.5
27.0
26.5
Siso/Nm (dB)
0
0.5
1
1.5
2
2.5
Ru thickness (nm)

FIG. 31

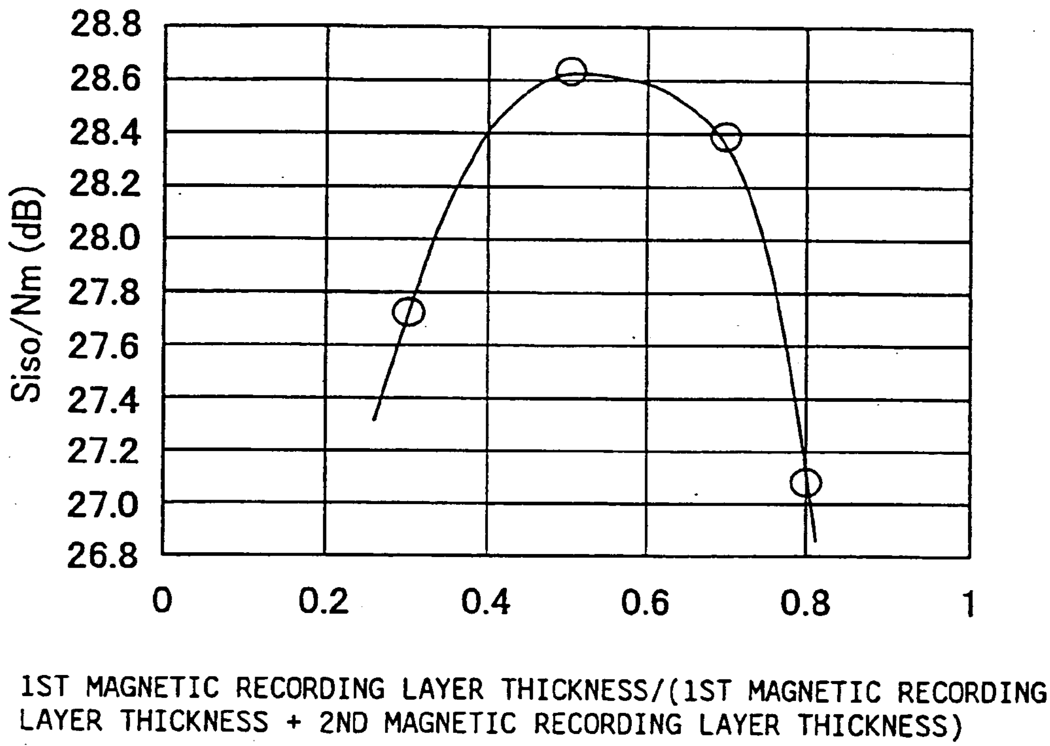
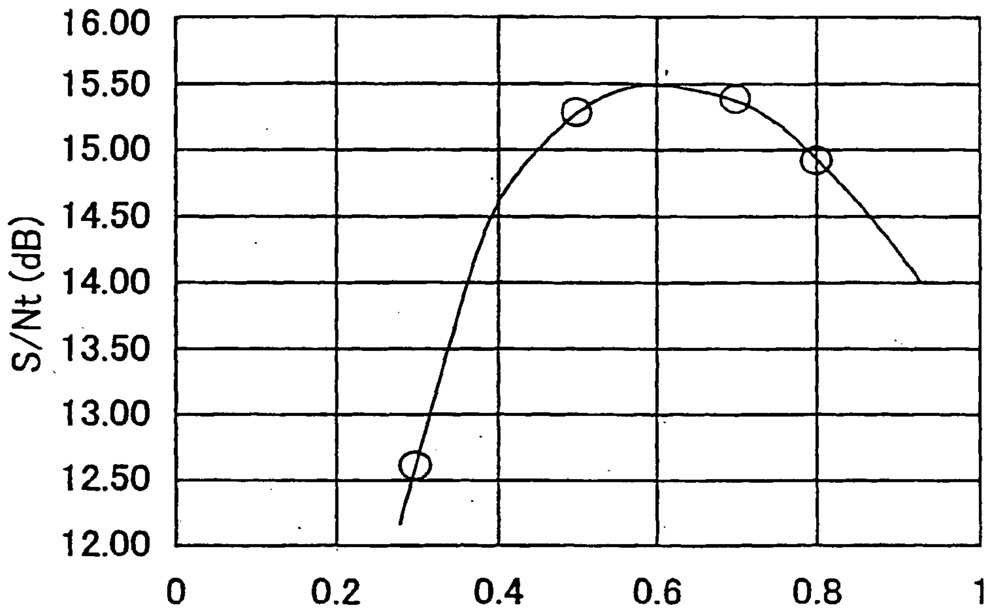

28.8
28.6
28.4
28.2
28.0
27.8
27.6
27.4
27.2
27.0
26.8
Siso/Nm (dB)
0
0.2
0.4
0.6
0.8
1
1ST MAGNETIC RECORDING LAYER THICKNESS/(1ST MAGNETIC RECORDING LAYER THICKNESS + 2ND MAGNETIC RECORDING LAYER THICKNESS)

FIG. 32



1ST MAGNETIC RECORDING LAYER THICKNESS/(1ST MAGNETIC RECORDING LAYER THICKNESS + 2ND MAGNETIC RECORDING LAYER THICKNESS)

FIG. 33